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# Experimental Study on the Static Ball Indentation Test of Wood.

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*With 21 text figures and plates I~ VI.*

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## INTRODUCTION

Various hardness indentation tests of material have been made since the eighteenth century, although it is at a comparatively recent date that they commenced to receive attention from a practical stand point.

The term "hardness" is often loosely applied and it seems to be extremely vague in its meaning. For instance, hardness may mean resistance to penetration as measured by static test, resilience as measured by dynamic test, scratching hardness, cutting hardness, abrasion hardness, or some other special kind of hardness. Unless this fact born in mind, there is likely to be confusion.

If each of these were a measure of the same definite property of the material, it is evident that the ratio of the result of any two kinds of test would be constant for every material tested. But according to the researches which have been published during recent year, it is by no means certain that these various kinds of hardness will be identical or even proportional to one another, although sometimes an approximate agreement may seem to exist between some kinds of hardness. If, therefore, such resistance, without qualification, be defined as the hardness of the material, it is evident that so-called hardness is no more a definite quality of a material, and consequently the discussion should always be separately considered.

Among the various kinds of hardness, indentation type is of great importance in connection with the material in load-resisting members and is generally defined as resistance to penetration in which the surface of the material under test is permanently distorted by the pressure of a hard steel ball, cone, or knife edge etc. and the test probably measures a group of properties of a fairly simple type.

Although we have the various methods which have been proposed for measurement of indentation hardness of material, the present investigation deals with the static ball indentation test of wood. There are many variables concerned with a complete study of this problem, but this paper is to report some of the results of microscopic and mechanical experiments which have been carried out by the present writer.

In conclusion, the writer wishes to express his hearty appreciation to Dr. K. OHARA for his helpful suggestion and criticism in relation to the submicroscopic structure of cell wall, to Mr. I. UTSUMI for the loan of valuable references, and to Mr. K. ISHIDA for his zealous assistance during the course of the work.

## HISTORICAL PRECEDENTS

A considerable amount of investigation has been done on the measurement of indentation hardness of materials but the method of determining this kind of hardness has been applied in three ways:

1. By mutual indentation or by testing material with itself.

2. By statically pressing an indenting tool of harder material into the material under test.
3. By producing the indentation by dropping a ball or conepoited hammer on to the material and measuring the rebound of the hammer or size of the indentation.

1. It is well known that RÉAUMUR in 1722 did work on the subject using right-angled prisms from two materials which were to be compared and pressed them together. The axes of the prisms were at right angles and the right-angled edges came into contact, forming a cross. (see fig. A). The relative hardness was measured by the relative depths of the mutual impressions.

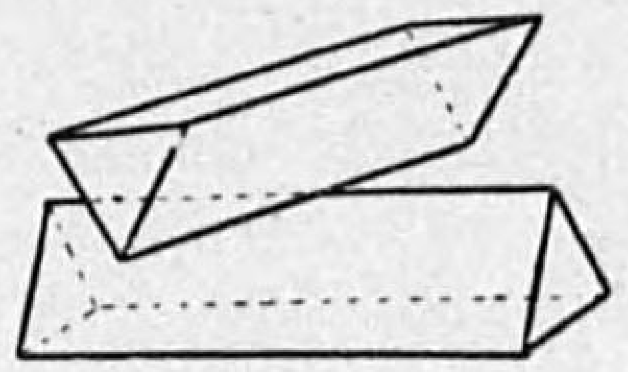

Fig. A.

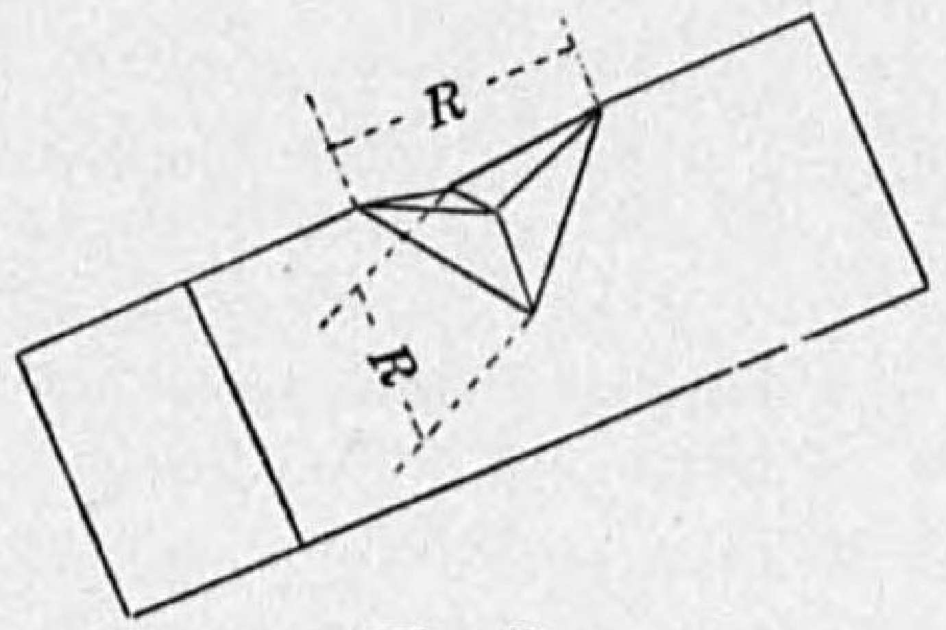

Fig. B.

A. FOEPPLE used two cyrindrical test pieces of the material whose hardness was required. This is the same method as RÉAUMUR's but only he changed the form of the test piece from prisms to cylinders. The two test pieces were placed one on the other, with axes at right angles, and were pressed together. FOEPPLE used the pressure per unit flattened surface as a measure of the indentation hardness, because he found that the surface of indentation was proportional to the pressure applied.

B. P. HAIGH(24) in 1920 re-introduced the mutual indentation test with the substitution of square for triangular prisms of RÉAUMUR. In this case, the hardness number is defined as $L/R^2$, where $L =$ the load and $R =$ the length of damaged edge of prism. (see fig. B). He pointed out the fact that when the prisms are alike in shape and hardness the indentations produced are of identical form and within reasonable ranges of load there is a constant proportionality between this load and the square of any linear dimention.

In 1930 I. H. Cowdrey(12) published the results of a research in which he modified Foepple's method by using parallel cylinders instead of crossed cylinders. He stated that over a wide range of material and hardness there is a constant relation between the Brinell hardness and the quotient obtained by dividing the applied load by the area of the mutual indentation produced by his method of test.

These hardness tests by mutual indentation are now not commonly applied, because of the necessity for the use of two test pieces at a time. There is, however, no limit to the hardness of the material which can be tested, as the test is independent of the use of a harder material as an indenting tool.

2. In the second type of indentation test, the material is tested by statically pressing with an indenting tool. Many different kinds of indenting tool have been tried and many ways have been suggested to express the relative indenting hardness.

Carvert and Johnson and Kirsch (1891) determined the load required to produce a permanent indentation of a given depth, whereas Carvert and Johnson used a trancated cone and a depth of 3.5 mm., Kirsch employed a cylindrical plunger of 5 mm. diameter and a depth of 0.01 mm.

The test adopted in 1856 by U. S. Ordance Department(75) was a determination of the volume of the indentation produced by a pyramidal point under a load of 10,000 lbs. A volume of 0.5 cubic inch was taken as unit hardness.

Middleberg (1886) used an indenting tool, in the form of a curved knife edge, for studying the hardness of tyres. The knife edge was 3/4 inch long, had an angle of 30°, and was formed with an edge curved to 1 inch radius. The reciprocal of the length of the indentation under a load of 6,000 lbs. was taken as a measure of the hardness.

Unwin (1897) also employed a knife edge, but in his case it was straight and consisted of a piece of hardened and ground 3/8 inch square steel, 1½ inches in length. Each tool thus had four indenting edges having angles of 90°. The material tested was formed into test bars ½″ × ½″ × ½″, and the knife edge was placed on the bar at right angles to its length, overlapping it by ½ inch on each side. The hardness number was taken as P/H, where P = the load in tons and H = the depth of the indentation in inches.

The method of test deviced by J. A. Brinell(9) in 1900 is now extensively employed. A hardened steel ball usually 10 mm. in diameter is pressed under a known load into the material to be tested, and the hardness number is taken as the stress per unit of spherical area. The loads used are usually 500, 1,000, or 3,000 kgs. The diameter of the indentation, or sometimes the depth is measured and the hardness number are obtained from tables furnished with the machines. The results are not absolutely accurate*, but give information of comparative value.

E. Meyer(47) used the projected area ($\pi d^2/4$) instead of the spherical area which is used in Brinell hardness. He stated that the reason why Brinell used the spherical area is not clear, as there does not appear to be any advantage gained by using it instead of the projected area. Anyhow, both of Brinell's and Meyer's methods have been very often applied to timber test. Many valuable investigations in relation to Brinell's or Meyer's methods of determining hardness have been done by C. Benedick(7) (1904), H, Le Chatelier(39) (1906), H. Moore(48) (1909), W. C. Unwin(73)(74) (1918), and many other investigators. But these were done in regard to metals.

M. Busgen(11) (1905) determined the hardness of 182 timbers by driving in a steel needle to a depth of 2 mm. The pressure in grammes necessary for this, devided by 100 was defined as hardness number. This method requires the careful choise of places for penetration and he confesses that Janka's method which will be described below is of more practical importance.

G. Janka(30) (1915) adopted the ball method for determining the hardness of wood. In his method, iron hemisphere 5.642 mm. in radius that is with maximum section $1\ \text{cm}^2$. is employed which is driven by continued pressure into planed surface of wood to be tested parallel to the grain until their maximum section lies in the plane of surface of wood. He concluded from his test that the hardness of wood diminishes with increasing moisture content, and so-

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* For very hard materials, the Brinell test is inaccurate, because of the distortion produced in the steel ball. Recently, Shore has carried out accurate Brinell tests on materials of superhardness by using a small diamond ball.

called "*Härtequotient*" is smaller in the wood of conifers and larger in the wood of broad-leaved species than so-called "*Qualitätquotient*". Furthermore he stated that coniferous timbers are more suitable for building purposes in which the greatest possible strength with the smallest possible specific gravity is important, whilst the hard wood are more suitable for uses such as furniture in which hardness and thus resistance to wear and tear are more important than lightness. Above conclusion drived by JANKA is considered to be merely analogical, for he did not carried out any abrasion test of timber. It has been clearly shown by SANITER (1908) that the ball-hardness number is not a safe guide to the power of a material to resist abrasion.

In order to overcome the variation in the Brinell hardness number with load and size of ball, LUDWICK(41) (1908) proposed substituting a 90° cone for the ball, and this form of indenting tool is now often used for the soft metals. The hardness number is obtained by means of this test in the same way as with Brinell test, i.e. the test load in kilograms is divided by the surface of the conical indentation in sq. mm., so that if $P =$ the load, and $d =$ diameter of indentation,

$$\text{Ludwick number} = \frac{P}{\pi\left(\frac{d}{2}\right)\times\left(\frac{d}{\sqrt{2}}\right)} = 0.9\left(\frac{P}{d^2}\right) \text{ approximately.}$$

With Ludwick's apparatus, the hardness number will be the same whatever the load chosen, if the material is homogeneous.

MEYER offered that in Ludwick test, the projected area is used instead of the surface area of the conical impression.

W. H. WARREN(76) (1911) adopted the method which follows the Brinell test for metals to measure the indentation hardness of timber, viz. a steel ball of fixed diameter is pressed into the surface of wood under a known load maintained for a stated time. WARREN used a ball of 20 mm., load of 1,000 kg., and time of 2 minutes. He found that the hardness along the fiber is considerably greater than either parallel or perpendicular to the annual ring. Another method adopted by WARREN, follows Ludwick test which has been rarely employed for timber. He used the standard 90° cone as an indenting tool and a pressure of 400 kg. applied for 1 minute. The depth was measured by an indicator as the test proceeded.

A method of ball indentation test of wood which is a modification of JANKA's method is now largely used in the United States of America. The method is to press a ball of 0.444 inch diameter* into timber until it has penetrated 0.222 inch. The test tool is a steel bar with a hemispherical end. This end projects through a hole in the bottom of a cup-shaped washer. When the tool has penetrated the timber to the correct depth there is binding between the steel bar, washer and specimen. The load at that instance is noted.

J. A. NEWLIN and T. R. C. WILSON (1917)(52) determined the hardness of many kinds of timbers by adopting the method just described above. According to them, there is no consistent difference between radial and tangential hardness, and end hardness is usually greater than side hardness.

Many kinds of machine have been developed for the purpose of the indentation test of materials, for instance Avery's Dead weight Brinell machine, Johnson Hardness testing machine, and many other small machines such as Brinall Pliers, Goodale and Bank's Baby Brinell, Dwarf's Brinell press, Schopper's "Seku" etc.

K. TANAKA (1926)(71) measured the Brinell hardness of some Japanese woods by adopting Schopper's "Seku". He applied the load of 100 kilograms except the soft species for which the load of 50 kilograms was applied. It should be noted that the hardness numbers which are obtained by different load shall not be compared unless these are reduced to a standard.

Dr. H. SHIRASAWA (1927)(69) determined the hardness number of many wood species grown in Japan and Eastern Asia**. In his method of testing, the steel cylinder with 3 cm. diameter hemispherical end was forced into the specimen ($6 \times 6 \times 6$ cm$^3$.) with the load of 2,000 kilograms against radial and tangential surfaces, and with 4,000 kilograms against end surface. In this case, as described above, the hardness number of end surface shall not be compared with that of longitudinal surface, because the load applied in each case is different.

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* The reason why 0.444 inch diameter ball is used is not clear, but since maximum section of this ball equals to 1 cm$^2$. approximately, the hardness number in this case represents lbs. per cm$^2$. of the projected area.

** Best thanks are due to Mr. S. MORI who has presented this table.

The hardness tester of ROCKWELL is essentially a machine that measures hardness by determining the depth of penetration of a penetrator into the specimen under certain arbitrarily fixed condition of test. The penetrator may be either a steel ball or a diamond cone. The hardness is expressed as a number which is obtained by subtracting the penetration from an established constant. A minor load of 10 kg. is first applied which causes an initial penetration which acts the penetrator on the material holding it into position. The dial is set at zero on the black-figure scale, and the major load is applied. This major load is customarily 60 kg. or 100 kg. when a steel ball is used as a penetrator, but other load may be used when found necessary, and 150 kg. when a diamond cone is employed. The ball penetrator is 1/16 inch in diameter normally but other penetrators of larger diameter such as ⅛ or ¼ inch may be employed for soft metals.

After the pointer comes to rest, the application of the major load is then removed leaving the minor load still applied to the specimen. The reciprocal of the amount of difference in penetration between the major and the minor load which is defined as hardness number is then revealed by the dial.

Another method which is known as VICKER's method, is to press a prism of diamond the top of which is 136° into the surface of metal to be tested. As in the case of Ludwick method, the impression in this case is always similar and the hardness will be independent of the load applied.

In most of the methods described above, considerably large impression is made to determine the hardness of indentation. Internal deformation of test piece, however, will vary with the size of impression produced, and consequently the resistance to the applied load will also vary. In order to decrease such variations of resistance, small load and small indentation are evidently being more preferred to large load and to large indentation. From this consideration, MARTENS defined the hardness of indentation as the load which is necessary to produce the impression of 0.05 mm. depth with a 5 mm. diameter steel ball.

Dr. T. MATSUMURA (1931) (45) defined a hardness number as the energy which is necessary to produce a given volume of impression on the surface of the material. In this method, he indented a diamond ball of 4 mm. diameter to the depth of $40\,\mu$. The energy per unit volume is taken as a hardness number of indentation. He derived the interesting result from his experiment of metals. In this study, he used the tetsing machine deviced by himself and gave it the name of "KATASA-METER". The energy per unit volume of indentation had already been used as a measure of hardness by F. WÜST and P. BARDENHEUER, and Dr. K. HONDA in dynamic hardness testing of metals which will be described later. Another method of test deviced by E. G. HERBERT(30) in 1923, was employed for measuring hardness by means of indentations. The instrument is called the pendulum hardness tester. A ball one millimeter in diameter is used in this instrument, the latter being in the form of a pendulum such that the ball can be put into contact with the material, the hardness of which is desired. The pendulum is made to oscillate, the time required for a given number of oscillations being taken as the measure of the hardness. The hardness number which is measured in this way is called time hardness.

According to HERBERT, there is a simple relation between time hardness ($T$) and the Brinell hardness ($H_B$):

$H_B = 10T$, where $T$ is greater than $33^1/_3$, and
$H_B = 0.3T$, where $T$ is less than $33^1/_3$.

The weight of the instrument is either two or four kilograms and therefore it can be used to determine the hardness of thin and fragile materials that otherwise could not be tested.

With this pendulum tester, sometimes another hardness number called "scale hardness" is taken as the measure of the hardness. The scale hardness is measured by the amount of an amplitude of an oscillation. This hardness may not always give the same value as the time hardness.

### 3. Impact or Dynamic Hardness.

Many methods have been deviced for measuring indentation hardness by the size of the indentation produced by energy of known amount. This method is complicated by a consideration of the effect of the rebound of indenting hammer, and there is a different opinion as to whether the initial energy of the blow or the net energy absorbed in producing the indentation should be considered in calculating the results.

A dynamic hardness test was pronounced by MARTEL in 1895. He used a pyramidal point as indenting tool, and produced the indentation by falling of a ram on to the material. According to **MARTEL**, the work of falling ram is proportional to the volume of the indent. He, therefore, expressed hardness as the work required to produce unit volume of indentation. He stated that for equal energies of blow the volume of the indentation was nearly the same, when using indenting tool of slight different form.

**BASTON** (1918) (4) carried out a series of experiments which confirmed **MARTEL**'s conclusion that the work of falling ram is proportional to the volume of the indent. According to **BASTON**, the dynamic hardness may be expressed by the energy in kg.-meters divided by the volume of the indentation in cubic centimeters.

A moving anvil block was supplied by W. and T. **AVERY** to adapt their Izod pendulum impact machine for dynamic hardness tests.

Ph. and F. **PELLIN** made a testing machine known as the Pellin Hardness testing Apparatus to determine the dynamic hardness of thin materials. The indentation is produced by a falling bar of known weight having at the lower end a steel ball 2.5 mm. in diameter.

Another instrument called the Auto Punch which is designed by Rudge Whitworth Ltd. is a convenient form of impact hardness tester though it was originally designed for testing case-hardened surfaces of metal.

Scleroscope is one of the best known form of dynamic hardness tester. In this test, the hardness is measured by the height of rebound of a small diamond pointed hammer about ¾ inch long and ¼ inch diameter, weighing $^1/_{12}$ oz. When this hammer is allowed to fall freely from a height of 10 inches, the height of rebound of the hammer is measured against a scale and is taken as a measure of hardness. The instrument is one which depend on the production of a permanent indentation by the diamond point, the rebound being diminished by the work expended in producing the indentation.

In this test, it should be noted that the character or condition of the material and of the surface affects the results. For instance, with rubber no permanent indentation is produced and the height of rebound is the same as that of a moderately hard steel, and also rubber and a certain wood may give the almost same rebound, even though they may differ in hardness. This instrument, therefore, may be less reliable for testing hardness of material like wood.

F. **WÜST** and P. **BARDENHEUER** (1920) (80) used the energy per unit volume of indentation to determine the impact hardness of metal and they derived the following relation between the energy ($E$) and the volume of deformation ($V$):

$$E = kV,$$

where $k$ is constant for materials.

Recently Dr. K. **HONDA** has carried out the experiment by adapting the Charpy pendulum impact machine for dynamic hardness test of metals at high temperature.

If $W$ = weight of the hammer, $h$ = initial height of the hammer, $h_1$ = the height of the rebound of the hammer, and $V$ = volume of indentation, the hardness number ($H_H$) will be represented by the expression:

$$H_H = W(h-h_1) / V.$$

As described above, various methods have been deviced and numerous investigations have been done in the test of indentation hardness of metals, yet compared with these, only a few has been done in regard to timber.

## IMPRESSION ON THE END SURFACE

Although we have now various kinds of test for determining indentation hardness of materials, in most cases, the hardness of wood has been determined either from the dimention of the indentation produced by a steel ball being pressed into the specimen to be tested under a given load, or from the load which produces a given size of ball impression on the surface of specimen. According to the former method, each size of ball impression and the corresponding deformation of internal region of wood usually varies with the properties of material tested, consequently the resistance of the material to the applied load may also vary. In this respect, it may be considered that the latter method is more reasonable than the former. In any case, however, if a steel ball is indented into a wood specimen, the surface of the spherical impression when the depth reaches a certain limit will begin to fail in shearing along the grain. After the failure takes place, the resistance of wood to indentation will change and consequently the wood block will not indicate its essential resistance. For this reason, the essential thing is that the wood block to be tested should not be broken by means of applied load.

In fact, it is very important that the hardness number of indentation should be obtained by the applied load and the corresponding deformation without any failure.

Moreover, the stress on the spherical surface of indentation is not uniformly distributed, especially when the depth of indentation increases, the distribution of stress may considerably vary according to the portion of the surface of indentation. And, since the hardness number is usually taken as average intensity of the pressure that is the stress per unit of spherical area or projected area, it is important to make an effort to get a fair average of stress which is unevenly distributed on the surface of the impression. For these reasons, it may be concluded that the less the indentation, the better the result. It is of course necessary in practice, to produce a permanent deformation which can be easily measured.

For the reasons described above, Janka's method which has been extensively employed for the hardness test of wood may not be pronounced reasonable. In his method, iron hemisphere 5.642 mm. in radius is driven by continued pressure into the surface of wood to be tested until the maximum section lies in the plane of original surface of wood. In such a case as this, it is quite natural that the fracture takes place on the surface of indentation. Pictures in his work(36), evidently show the line of fracture due to excessive penetration, in other words, these pictures show that his hardness test was not carried out rationally.

As has been described, if a steel ball is indented into a wood block, the surface of the spherical impression when the depth reaches a certain limit will begin to fail and consequently no exact hardness number can be obtained. In such a test, therefore, the depth of indentation should be less than a certain limit. This limit is known as the critical depth of indentation. Hence the critical depth of indentation is defined to be the maximum depth of impression that can be produced by penetrating a ball of given size into the material to be tested without causing any fracture.

In order to find the critical depth of indentation of various wood species, the experiment was carried out as follows.

In the first place, 10 mm. steel ball was indented into clearly planned surface of wood block, until 2.5 mm. of depth reached. 136 test blocks including 12 species of wood described below were examined and it was found that every specimen tested was completely failed without exception. In this case, the line of failure clearly appears as somewhat irregular shaped closed curve along the periphery of the spherical impression as shown in fig. 1 and fig. 2. This shows that 2.5 mm. of depth is excessive for such a ball indentation test of wood.

The testing machine used in the present study was Pittsburg, Brinell Machine style "A", and the materials were tested in air dry condition. The species of wood tested were as follows:

*Karamatsu*, *Momi*, *Tsuga*, *Sugi*,
*Hinoki*, *Shirakashi*, *Keyaki*, *Hohnoki*,
*Katsura*, *Kihada*, *Harigiri*, *Kiri*,

Common and botanical names of wood species used in the present study are given in the list of page 69.

In the second place, in order to find at what depth the initial fracture occurs, various depths of impression were made on the end surface of wood and each impression was carefully inspected. The results obtained are shown in the Table I.

Abbreviations used in the following table are:

*Sp.gr.* = specific gravity,
*R/cm.* = ring per cm.,
*tg.* = tangential line of fracture,
*r.* = radial line of fracture,
*tg. r.* = *tg.* accompanied by *r.*,
*r. tg.* = *r.* accompanied by *tg.*

TABLE I.

i. *Karamatsu.*

| Sp. gr. | R/cm. | Depth (mm. $\times 10^{-2}$) | Fracture |
|---|---|---|---|
| .51 | 3.4 | 140 | + tg. |
| .53 | 3.6 | 131 | + tg. |
| .51 | 3.2 | 130 | + tg. |
| .53 | 3.5 | 130 | — |

TABLE I. (*Continued*)

i. *Karamatsu.*

| Sp. gr. | R/cm. | Depth (mm. ×10⁻²) | Fracture |
|---|---|---|---|
| .51 | 3.3 | 130 | + tg. |
| .53 | 3.7 | 122 | + tg. |
| .54 | 3.6 | 121 | + tg. |
| .53 | 3.5 | 120 | – |
| .53 | 3.4 | 120 | + tg. |
| .51 | 3.2 | 120 | + tg. |
| .54 | 3.4 | 111 | + tg. |
| .54 | 3.2 | 110 | – |
| .54 | 3.2 | 110 | + tg. |
| .52 | 3.3 | 109 | + tg. |
| .54 | 3.4 | 105 | – |
| .53 | 3.5 | 103 | – |
| .53 | 3.4 | 101 | – |
| .53 | 3.4 | 100 | – |
| .52 | 3.3 | 100 | – |
| .52 | 3.2 | 100 | – |
| .52 | 3.3 | 100 | – |
| .51 | 3.7 | 98 | – |
| .52 | 3.2 | 98 | – |
| .51 | 2.0 | 97 | – |
| ii. *Momi.* | | | |
| .30 | 6.3 | 130 | + tg. r. |
| .32 | 9.3 | 122 | + tg. |
| .34 | 8.4 | 118 | + tg. |
| .29 | 8.2 | 112 | + tg. r. |
| .32 | 10.0 | 102 | + tg. |
| .32 | 10.4 | 102 | + tg. |
| .29 | 14.0 | 100 | + tg. |
| .29 | 11.3 | 100 | + tg r. |
| .29 | 8.5 | 99 | + tg. |
| .30 | 6.5 | 98 | + tg. |
| .32 | 7.8 | 81 | + tg. |
| .32 | 8.0 | 80 | + tg. |
| .30 | 6.7 | 70 | + tg. |

TABLE I. (*Continued*)

ii. *Momi.*

| Sp. gr. | R/cm. | Depth (mm. ×10⁻²) | Fracture |
|---|---|---|---|
| .29 | 10.9 | 67 | – |
| .30 | 6.7 | 65 | – |
| .32 | 8.3 | 64 | + tg. |
| .30 | 6.6 | 63 | – |
| .34 | 6.3 | 62 | – |
| .34 | 6.3 | 62 | – |
| .34 | 6.9 | 60 | – |
| .34 | 6.5 | 60 | – |
| .30 | 12.6 | 58 | – |
| .32 | 10.8 | 58 | – |
| .30 | 10.0 | 56 | – |
| iii. *Tsuga.* | | | |
| .45 | 8.0 | 130 | + tg. |
| .45 | 9.0 | 122 | + tg. |
| .56 | 11.0 | 121 | + tg. |
| .44 | 5.0 | 120 | + tg. |
| .44 | 5.0 | 120 | + tg. |
| .41 | 9.0 | 112 | + tg. |
| .45 | 9.0 | 112 | + tg. |
| .39 | 7.0 | 111 | + tg. |
| .56 | 10.0 | 110 | + tg. |
| .45 | 9.0 | 110 | + tg. |
| .41 | 12.2 | 110 | – |
| .44 | 6.5 | 105 | + tg. |
| .44 | 6.4 | 105 | – |
| .45 | 9.0 | 105 | + tg. |
| .39 | 6.0 | 101 | – |
| .44 | 4.0 | 101 | – |
| ,39 | 12.1 | 100 | – |
| .44 | 4.2 | 100 | – |
| .50 | 11.0 | 100 | – |
| .41 | 9.0 | 100 | – |
| .45 | 9.0 | 100 | – |
| .44 | 6.5 | 98 | – |

TABLE I. (*Continued*)

iv. *Sugi.*

| Sp. gr. | R/cm. | Depth (mm. ×10⁻²) | Fracture |
|---|---|---|---|
| .36 | 1.6 | 140 | + tg. r. |
| .36 | 1.6 | 135 | + tg. |
| .34 | 3.4 | 122 | — |
| .38 | 3.6 | 120 | + tg. |
| .34 | 2.8 | 102 | — |
| .36 | 1.6 | 100 | + tg. |
| .32 | 1.6 | 92 | — |
| .32 | 1.8 | 90 | + tg. |
| .32 | 1.6 | 90 | — |
| .34 | 4.2 | 90 | + tg. |
| .39 | 7.0 | 81 | + tg. |
| .39 | 4.2 | 81 | + tg. |
| .39 | 7.0 | 80 | + tg. |
| .39 | 3.3 | 80 | — |
| .36 | 1.7 | 77 | + tg. |
| .32 | 1.8 | 75 | + tg. |
| .39 | 6.0 | 73 | — |
| .34 | 4.2 | 71 | — |
| 36 | 1.6 | 70 | — |
| .39 | 3.3 | 70 | — |
| .38 | 2.7 | 70 | — |
| .39 | 3.3 | 70 | — |
| .38 | 2.7 | 69 | — |
| .38 | 2.8 | 68 | — |

v. *Hinoki.*

| Sp. gr. | R/cm. | Depth (mm. ×10⁻²) | Fracture |
|---|---|---|---|
| .43 | 2.1 | 140 | + r. tg. |
| .43 | 1.9 | 132 | + r. |
| .53 | 2.9 | 132 | + r. tg. |
| .55 | 3.0 | 132 | + r. |
| .42 | 3.0 | 131 | + r. |
| .51 | 3.0 | 131 | — |
| .53 | 2.8 | 130 | + r. |
| .51 | 2.9 | 128 | — |
| .55 | 2.0 | 121 | + tg. |

TABLE I. (*Continued*)

v. *Hinoki.*

| Sp. gr. | R/cm. | Depth (mm. ×10⁻²) | Fracture |
|---|---|---|---|
| .55 | 3.0 | 121 | — |
| .47 | 4.3 | 115 | + tg. r. |
| .42 | 3.1 | 112 | — |
| .52 | 3.0 | 105 | + r. |
| .47 | 3.9 | 104 | + r. |
| .42 | 3.1 | 104 | + r. |
| .47 | 4.3 | 102 | + r. tg. |
| .45 | 4.0 | 102 | — |
| .53 | 2.5 | 92 | — |
| .53 | 2.5 | 92 | — |
| .47 | 4.2 | 91 | — |
| .53 | 3.0 | 91 | — |
| .52 | 3. | 91 | — |
| .42 | 3.1 | 90 | — |
| .45 | 4.2 | 90 | — |

vi. *Shirakashi.*

| Sp. gr. | R/cm. | Depth (mm. ×10⁻²) | Fracture |
|---|---|---|---|
| .86 | 5.8 | 162 | + tg. |
| .87 | 4.2 | 152 | + tg. |
| .86 | 4.9 | 151 | + tg. |
| .86 | 4.0 | 151 | + tg. |
| .87 | 4.2 | 150 | + tg. |
| .86 | 6.6 | 150 | — |
| .86 | 6.5 | 150 | + tg. |
| .86 | 5.8 | 145 | — |
| .86 | 5.5 | 141 | — |
| .84 | 4.7 | 141 | + tg. |
| .86 | 6.5 | 140 | — |
| .86 | 4.6 | 140 | + tg. |
| .86 | 4.7 | 140 | — |
| .86 | 5.5 | 140 | — |
| .87 | 4.2 | 138 | — |
| .84 | 4.0 | 138 | — |
| .86 | 4.5 | 135 | — |
| .87 | 4.0 | 133 | — |

TABLE I. (*Continued*)

vi. *Shirakashi.*

| Sp. gr. | R/cm. | Depth (mm. $\times 10^{-2}$) | Fracture |
|---|---|---|---|
| .86 | 4.5 | 133 | — |
| .86 | 4.5 | 132 | — |
| .85 | 4.0 | 131 | — |
| .86 | 5.3 | 130 | — |
| .86 | 4.8 | 130 | — |
| .86 | 4.5 | 130 | — |

vii. *Keyaki.*

| | | | |
|---|---|---|---|
| .64 | 10.5 | 182 | + tg. |
| .65 | 6.6 | 175 | + tg. |
| .63 | 11.5 | 172 | — |
| .64 | 8.0 | 172 | + tg. |
| .64 | 10.0 | 169 | + tg. |
| .58 | 10.0 | 162 | — |
| .64 | 6.6 | 162 | + tg. |
| .64 | 6.0 | 162 | + tg. |
| .58 | 8.0 | 161 | + tg. |
| .64 | 6.0 | 161 | + tg. |
| .64 | 8.0 | 155 | + tg. |
| .59 | 10.0 | 151 | + tg. r. |
| .64 | 7.3 | 151 | — |
| .58 | 12.5 | 151 | — |
| .59 | 10.0 | 150 | — |
| .64 | 6.0 | 150 | — |
| .64 | 7.5 | 145 | — |
| .64 | 7.6 | 142 | — |
| .64 | 6.6 | 142 | — |
| .64 | 6.5 | 140 | — |
| .70 | 4.0 | 140 | — |
| .70 | 5.7 | 140 | — |
| .64 | 8.0 | 135 | — |
| .58 | 8.0 | 135 | — |

TABLE I. (*Continued*)

viii. *Hohnoki.*

| Sp. gr. | R/cm. | Depth (mm. $\times 10^{-2}$) | Fracture |
|---|---|---|---|
| .48 | 4.8 | 101 | + r. |
| .46 | 5.8 | 91 | — |
| .48 | 6.0 | 90 | + r. |
| .46 | 5.8 | 90 | + r. |
| .46 | 9.7 | 83 | — |
| .47 | 8.2 | 83 | + r. |
| .46 | 4.4 | 83 | + r. |
| .48 | 9.5 | 82 | + r. |
| .47 | 5.0 | 81 | + r. |
| .50 | 4.0 | 81 | + r. |
| .50 | 4.2 | 81 | + r. |
| .48 | 5.0 | 81 | — |
| .48 | 9.5 | 75 | + r. |
| .47 | 4.7 | 73 | + r. |
| .50 | 4.2 | 73 | — |
| .50 | 4.4 | 72 | — |
| .48 | 6.0 | 70 | — |
| .47 | — | 70 | — |
| .47 | 4.7 | 68 | — |
| .46 | 8.2 | 65 | — |
| .48 | 4.8 | 63 | — |
| .47 | 5.5 | 62 | — |
| .48 | 5.0 | 62 | — |
| .46 | 9.3 | 61 | — |

ix. *Katsura.*

| | | | |
|---|---|---|---|
| .52 | 6.4 | 113 | + r. |
| 53 | 5.8 | 107 | + r. |
| .52 | 6.3 | 101 | + r |
| .54 | 5.3 | 101 | + r. |
| .54 | 5.0 | 100 | + r |
| .54 | 7.0 | 99 | — |
| .53 | 6.5 | 97 | + r |
| .52 | 5.0 | 92 | + r |
| .53 | 5.8 | 90 | + r |

TABLE I. (*Continued*)

ix. *Katsura.*

| Sp. gr. | R/cm. | Depth (mm. ×$10^{-2}$) | Fracture |
|---|---|---|---|
| .53 | 6.3 | 85 | + r. |
| .53 | 6.0 | 85 | + r. |
| .53 | 5.0 | 82 | — |
| .52 | 5.3 | 81 | — |
| .53 | 5.8 | 80 | — |
| .53 | 5.4 | 80 | — |
| .53 | 6.5 | 80 | — |
| .53 | 6.5 | 78 | — |
| .53 | 6.8 | 75 | — |
| .52 | 4.4 | 73 | — |
| .52 | 4.1 | 72 | — |
| .53 | 6.0 | 70 | — |
| .52 | 5.5 | 70 | — |
| x. *Kihada.* | | | |
| .52 | 1.7 | 151 | + r. |
| .52 | 1.4 | 142 | + r. |
| .55 | 3.0 | 142 | + r. tg. |
| .55 | 4.0 | 129 | + r. tg. |
| .44 | 2.5 | 120 | + r. |
| .56 | 2.6 | 120 | + r. |
| .55 | 3.7 | 115 | + r. tg. |
| .55 | — | 110 | + tg. |
| .55 | 2.5 | 103 | — |
| .56 | 2.6 | 102 | + tg. |
| .44 | 2.6 | 101 | — |
| .55 | 3.7 | 101 | + tg. |
| .55 | 3.3 | 100 | — |
| .56 | 3.6 | 100 | + tg. |
| .53 | 3.7 | 100 | + tg. |
| .53 | 4.1 | 100 | + tg. |
| .53 | 4.0 | 95 | + tg. |
| .52 | 2.3 | 93 | — |
| .52 | 3.8 | 92 | — |
| .53 | 4.0 | 92 | — |

TABLE I. (*Continued*)

x. *Kihada.*

| Sp. gr. | R/cm. | Depth (mm. ×$10^{-2}$) | Fracture |
|---|---|---|---|
| .53 | 4.2 | 91 | — |
| .52 | 3.1 | 91 | — |
| .52 | 2.3 | 90 | — |
| .52 | 3.7 | 89 | — |
| xi. *Harigiri.* | | | |
| .53 | 4.7 | 124 | + tg. |
| .53 | 7.1 | 123 | + tg. |
| .52 | 6.0 | 122 | + tg. |
| .53 | 6.2 | 122 | + tg. |
| .52 | 7.5 | 122 | + tg. |
| .53 | 5.0 | 121 | + tg. |
| .53 | 5.2 | 121 | + tg. |
| .53 | 5.2 | 120 | + tg. |
| .52 | 6.0 | 115 | + tg. |
| .57 | 5.7 | 113 | + tg. |
| .57 | 5.7 | 112 | — |
| .52 | 7.5 | 112 | — |
| .52 | 6.0 | 111 | — |
| .57 | 5.6 | 111 | — |
| .52 | 6.0 | 110 | — |
| .52 | 6.0 | 110 | — |
| .53 | 5.2 | 110 | — |
| .53 | 4.7 | 108 | — |
| .52 | 6.0 | 105 | — |
| .53 | 4.5 | 103 | — |
| .53 | 5.2 | 102 | — |
| .57 | 8.9 | 100 | — |

TABLE I. (*Continued*)

xii. *Kiri.*

| Sp. gr. | R/cm. | Depth (mm. $\times 10^{-2}$) | Fracture |
|---|---|---|---|
| .31 | 1.0 | 121 | + tg. |
| .21 | 1.1 | 119 | + tg. |
| .31 | 1.0 | 110 | + tg. |
| .33 | 0.9 | 105 | + tg. |
| .22 | 1.0 | 102 | + tg. |
| .22 | 1.1 | 102 | + tg. |
| .33 | 1.0 | 102 | — |
| .34 | 1.1 | 100 | + tg. |
| .33 | 1.0 | 91 | — |
| .33 | 1.0 | 90 | — |
| .33 | 1.1 | 90 | + tg. |
| .33 | 1.1 | 85 | + tg. |
| .33 | 0.9 | 85 | + tg. |
| .31 | 1.1 | 80 | + tg. |
| .31 | 1.0 | 79 | + tg. |
| .33 | 1.0 | 70 | — |
| .21 | 1.1 | 68 | — |
| .21 | 0.9 | 67 | — |
| .21 | 0.9 | 66 | — |
| .34 | 1.0 | 66 | — |
| .31 | 1.0 | 65 | — |
| .34 | 1.0 | 65 | — |
| .33 | 1.2 | 63 | — |
| .34 | 1.1 | 62 | — |

The observation shows that the critical depth of indentation considerably varies according to the different species of wood, but within a species the value of critical depth seems to be confined within a certain range, although there was a few exception. From these data, the critical depth of indentation in each wood species may be estimated approximately as Table II.

It should be noted that the critical depth of indentation considerably varies not only with the properties of individual block but also with diameter of ball to be used and the speed of loading, consequently the value of critical depth given in the Table II may be not always constant for a given species.

TABLE II.

| Species. | Sp. gr. (average) | R/cm. (average) | Critical depth. (mm. $\times 10^{-2}$) | Typical fracture. |
|---|---|---|---|---|
| *Karamatsu.* | 0.53 | 3.33 | 100–105 | tg. |
| *Mori.* | 0.31 | 8.65 | 60–65 | tg. |
| *Tsuga.* | 0.45 | 8.09 | about 100 | tg. |
| *Sugi.* | 0.36 | 3.14 | about 70 | tg. |
| *Hinoki.* | 0.49 | 3.11 | 90–95 | r. |
| *Shirakashi.* | 0.86 | 4.91 | 130–140 | tg. |
| *Keyaki.* | 0.63 | 7.95 | 140–150 | tg. |
| *Hohnoki.* | 0.48 | 6.03 | 60–70 | r. |
| *Katsura.* | 0.53 | 5.78 | 70–80 | r. |
| *Kihada.* | 0.55 | 3.28 | about 90 | tg. or r. |
| *Harigiri.* | 0.53 | 5.90 | about 110 | tg. |
| *Kiri.* | 0.30 | 1.03 | 60–70 | tg. |

Anyhow, in Brinell, or Meyer or any other methods of testing, it is very dangerous to apply an arbitrary load, and the load should be applied within a certain limit of depth.

When a steel ball is indented into the surface of material, the periphery of the impression does not always lie in the original surface. Sometimes the edge of the periphery extrudes or intrudes as shown in fig. C. It is, therefore, quite important to note the condition of the edge of impression in computation of the spherical area.

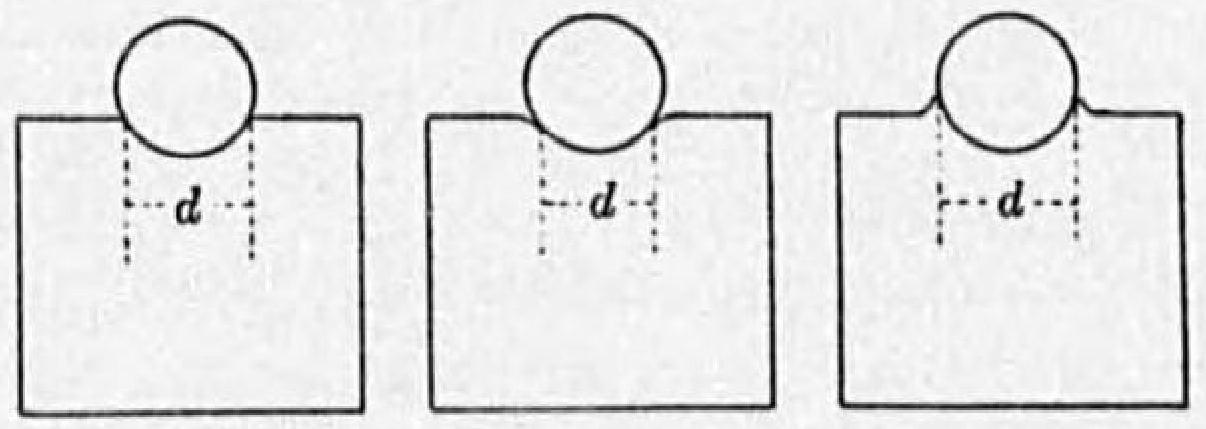

Fig. C.

The diameter of impression (d) is usually measured by a simply constructed micrometer microscope but sometimes in order to obtain the results more accurately, it is measured by a comparator. Sometimes, in order to dispense with the use of such instruments, the depth of indentation can be measured during the test by means of some form of depth indicator. The depth is measured relatively to the original surface of the test piece. This often excludes the effect of extrusion or intrusion round the indentation, but the hardness number found in this way may not be always identical or proportional to that obtained in the usual way from the diameter. It should be noted that the diameter of the ball impression is usually measured after the applied load is released, while the depth is usually measured during the test.

According to the investigation done by Dr. K. Honda(33), in the case of hard metals, Brinell number obtained from the diameter is much higher than that from the depth, although in soft metals this difference is not so distinct. In such a test, it is more reasonable to measure the amount of deformation during the test than to measure it after load is released. This reason may be easily understood when we consider the deformation of the extremely elastic material such as rubber. After the load is released the amount of deformation of rubber can not be measured, in other words, the Brinell number in this case is infinity great which is doubtlessly unreasonable.

On the end surface of wood, however, the difference between the hardness number obtained from the diameter and that from the depth was found to be not distinct. Moreover, the periphery of the ball impression practically lies in the original surface, especially when the impression is comparatively small, in other words, the extrusion and intrusion round the impression is practically negligible. Therefore, on the end surface of wood the hardness number may be almost equally determined by basing the computation either upon the depth or the diameter.

## IMPRESSION ON THE RADIAL SURFACE

On the longitudinal surface of wood, the ball impression which is remained after loading, has a quite different aspect from that of the end surface. In this case, the edge of the impression shows a remarkable intrusion and shows somewhat elliptic projection whose minor axis is in the direction parallel to the grain. This may be explained as follows. In penetrating a ball, the fibers on the end grained sides bring about more remarkable intrusion than those on the lateral sides do, and consequence, the ball penetrated is in much less contact with the surface of wood along the grain than across the grain.

When the depth increases until some of the fiber walls are crosswisely broken, the impression shows more or less spherical or sometimes elliptic projection which is rather elongated along the grain.

Since the intrusion of the edge of impression on the longitudinal surface of wood is considerably remarkable, the boundary of the impression is not distinct, consequently it is almost impossible to measure the diameter of impression exactly. In this case, computation of the hardness number will be based upon the depth of impression instead of the diameter. But, since the impression does not usually indicate the geometrical ellipsoid, it is very difficult to obtain either the area of concaved surface or pojected area of impression, even if the exact depth is measured.

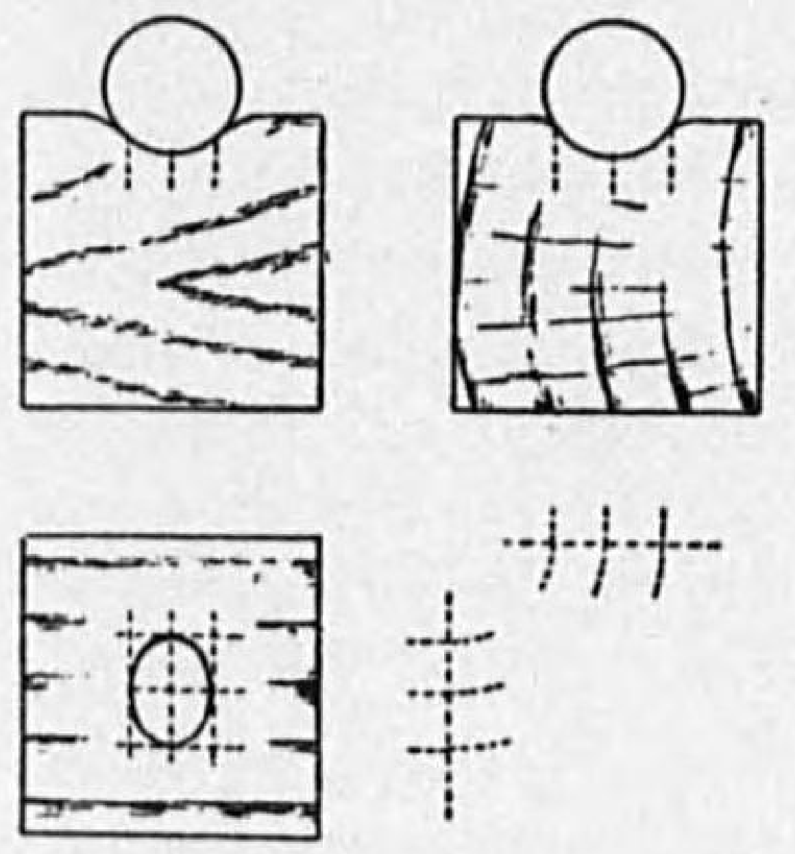

Fig. D.

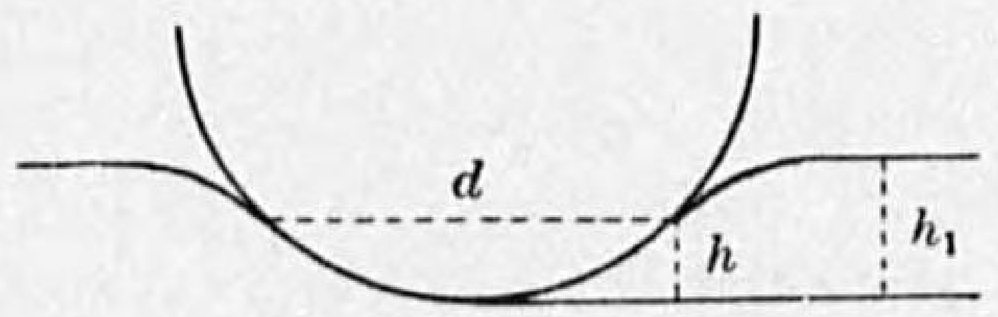

Fig. E.

In such a case as above, the depth which is measured is $h_1$, and not $h$. (see fig. E). It is important to note that owing to the intrusion of the edge of indentation, $h_1$ is not equal to $h$, and at the same time the amount of this side intrusion is not the same with different materials under similar conditions, consequently the ratio of $h_1/h$ is not always constant. It therefore follows that the hardness number of indentation obtained in this way is not the hardness number defined by Brinell or Meyer. Although many hardness numbers of indentation of the longitudinal surface of wood have been reported as the result of experiments, it is doubtful that they were determined by taking such a condition as above into consideration.

In the test of metals, when the projection of ball impression does not show true circle, the hardness number of indentation is usually obtained by basing the computation on the mean diameter. In the case of the longitudinal surface of wood, unfortunately, the periphery of the elliptic impression does not lie in the same plane. It is, therefore, very difficult to obtain the required area. But, for convenience sake, provided that the projection of the impression shows the geometrical ellipse and the periphery lies in the same plane, the Meyer's hardness number of indentation of the side grain may be obtained approximately as follows:

$$H_M = P/(\pi ab),$$

where $H_M$ = Meyer's hardness number, $P$ = applied load, and $a$ and $b$ are semi-major and semi-minor axes respectively.

It is of course necessary that the hardness number described above shall be obtained within the critical depth of indentation.

In cast metals having a fairly coarse structure the form of impression may be visible irregular, but the mean diameter and the area of the corresponding spherical indentation is calculated for the purpose of obtaining the hardness number.

In fact, even in the case of end surface of wood, sometimes, especially in ring porous species, true circle is not maintained by the ball indentation. Therefore, the computation of obtaining the hardness number of end surface of wood shall be also based on the mean diameter as in the case of the cast metals.

## MANNER OF FRACTURE AT INITIAL STAGE

As has already been described, on the end surface of wood block, when the depth of indentation exceeds a certain limit, the fracture will take place on the surface of impression. It is very interesting to note that the gross feature of fracture at the initial stage appears to be closely related with the anatomical feature of each wood species.

As the depth of ball indentation increases, the fracture starts at a point of high localized stress or at a point of weakness, and gradually spreads toward the rest region of the surface of impression and at last forms an irregular closed curve along the periphery of the ball impression. The gross feature of this irregular curve is almost similar irrespective of wood species as shown in Pl. I. (fig. 1 and fig. 2). The pictures shown in JANKA's work(36) clearly show the line of fracture just the same as described above.

In the present study, the manner of fracture at the initial stage in each wood species tested was observed as follows.

*Katsura* (*Cercidiphyllum japonicum*) and *Hohnoki* (*Magnolia obovata*) are of diffuse porous type and the distribution of their vessels are almost uniform, and diffused rays seem to form the weak zone of the tissue. In fact, in these species, the line of fracture usually takes place as radial line along the wood rays, though sometimes it appears more or less diagonally.

As the applied load is increased, the line of fracture gradually developes and at last forms the irregular closed curve as described before.

Every diffuse porous species which has diffuse ray does not always show the same manner as above species. For instance, in Japanese box wood (*Buxus japonica*), the slight wavy lines appear more or less parallel to the annual ring, but no radial line along the wood ray will appear unless considerable amount of load is applied.

*Shira-kashi* (*Quercus myrsinaefolia*)—ever green broad leaved species, is of a radial porous type where the vessels in radial line are usually solitary. In such a case as this, at first glance, it might be expected that the initial fracture will take place along the radial line of pores, yet it occurs not so but as tangential line.

This is obviously due to the zone of weakness formed by the zonate parenchyma, and it is worthy to note that the initial fracture does not usually take place along the radial line of pores in this species.

*Keyaki* (*Zerkowa serrata*) and *Harigiri* (*Kalopanax ricinifolium*) are of ring porous type and the vessels in their summer wood are arranged in tangential wavy line or festoon type running across the rays just like in Elm species. In these two species, the line of fracture usually takes place along the porous ring and very often as diagonal or wavy line along the festoon type of pores in summer wood.

In *Kihada* (*Phellodendron amurence*), the manner of initial fracture is more or less similar to above two species though it is not so regular. In this species, the line of fracture often takes place as tangential wavy line along the zonate parenchyma, or as tangential line along the porous ring or sometimes as radial line along the wood ray.

In *Kiri* (*Paulownia tomntosa*) which is of ring porous type and has remarkable paratracheal zonate parenchyma, the line of fracture takes place as tangential line either along the zone of parenchyma or pores ring, as might be expected.

In coniferous woods, *Momi* (*Abies firma*), *Tsuga* (*Tsuga Sieboldii*), *Sugi* (*Cryptomeria japonica*), *Hinoki* (*Chamaecyparis obtusa*) and *Karamatsu* (*Larix Kaempferi*) were examined. In most of these species, the initial fracture appears as tangential line along the boundary between spring and summer wood excepting *Chamaecyparis obtusa* in which the line of fracture usually takes place along the wood ray. Sometimes, in *Sugi* and *Momi*, the tangential line of fracture is often accompanied by the radial line of fracture especially in the case of deep penetration.

The fact that the initial fracture takes place along the boundary of the annual ring may result from the obvious difference between the spring wood and summer wood tissue.

The line of fracture on the longitudinal surface of wood, does not usually indicate so distinct characteristics as in the case of end surface.

In this case, within the critical depth of indentation, the impression will show an elliptic projection which has a minor axis along the grain of wood. Beyond the critical depth, however, the fiber walls are often broken crosswisely or sometimes torn obliquely or sometimes separations take place along the walls in the vicinity of the edge of the impression. This manner of fracture was found to be almost true of all the woods studied irrespective of species.

## REGIONAL SPREAD OF DEFORMATION IN THE INTERNAL PORTION OF WOOD

It is not only interesting but also important to know the manner of deformation in the internal region of wood due to ball indentation. In order to know this manner, observation was made on the longitudinal section cut through the center of the concaved surface of impression. The observation shows that the deformed region is less lustrous than the unaltered portion and consequently the injured part is almost distinctly recognized by unaided eye and in most cases, the regional spread of the deformation of wood element is comparatively regular as shown in fig. 3～10. These figures were made by means of Sump pressing method.

In radial surface of some woods such as *Karamatsu, Sugi, Momi* and *Tsuga*, the margin of injured region appears somewhat irregularly. (see fig. 6 and 7). It may be due to the obvious difference between the spring wood and the summer wood.

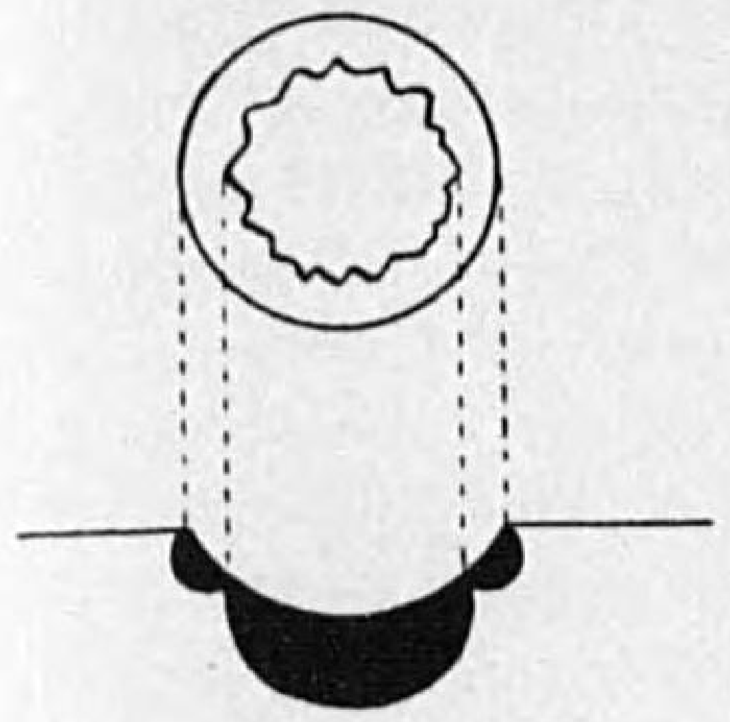

Fig. F.

When the depth of indentation reaches a certain limit, the surface of the impression will begin to fail in shearing along the longitudinal direction of fiber.

After the fracture takes place due to excessive penetration, the area of the injured part will have a widely different aspect as shown in fig. F, as well as fig. 4.

In this case, the deformed region is divided into two separated parts, one is the outer part and the other is the inner part of the zone of shearing.

It is doubtlessly unreasonable that the hardness number of indentation is represented by the average intensity of the applied load per unit spherical or projected area of such a false impression as above. Hence, Janka's method in which the fracture will decidedly take place due to excessive penetration in any wood species can not be said reasonable for determining the indentation hardness of wood.

## LUEDERS' LINE

So long as the material remains in the elastic stage, or rather until the yield-point is reached, there is no visible change in the appearance of the surface. As soon as, however, the yield-point is reached and permanent deformation occurs, definite changes are seen to take place on the surface. Such deformation consist in sliding of considerable portions of the specimen along planes inclined about 45° to the axis of specimen, i.e. along the planes in which the shearing stress is a maximum.

These planes of sliding usually begin at points of stress concentration and they are revealed on the surface by easily discernible lines, if the surface of specimen is clearly planed.

These lines appear, at first in isolated group, but in steadily increasing numbers until the surface are cross-hatched with fine lines, and usually form a special figure which is known as LUEDERS' line. Sometimes this pattern is called HARTMANN's line, for the manners of the pattern in various cases were investigated by HARTMANN. The LUEDERS' lines often take place on the surface of wood though the yield point of wood is not distinct. Many investigations in regard to mechanical test of wood have been made, but work concerns the LUEDERS' line of wood has been scarcely reported.

Though the present investigation was made in regard to ball indentation test of wood, the Lueders' line due to end compression may be useful to mention here briefly to serve as a reference.

The Lueders' line due to end compression parallel to the grain very often appears as a system of straight lines extending across the longitudinal axis of wood at 45° to 70°. The slope is in either direction and these lines cross each other, forming fine cross hatching. (see fig. 13∼16).

There seems to be a certain variation between the manner of line and the wood species. The observation shows that in some hardwoods such as *Kihada*, *Keyaki*, *Maguwa* and *Shii*, fine straight lines which densely cross each other were recognized, while in *Hohonoki* and *Katsura*, distribution of these lines were not so dense as above species and in these latter species, each line is more or less irregular or step-like and often branched. In most coniferous woods tested, these lines appear somewhat like those of *Hohonoki*, but in the summer wood of *Tsuga* and *Karamatsu*, it was often observed that the straight crossed lines are more or less coarsely distributed.

As a rule, in the hard summer wood zone of ring porous wood, these cross hatching lines seem to be produced densely and regularly. Lueders' line of ring porous wood due to end compression are shown in fig. 15 and 16, which are photographed by using "Ultropak objective". As these lines consist principally of the minute folding of the fiber wall, they may more or less differ from the Lueders' line of metals. Indeed, the Lueders' line of wood is a kind of localized deformation which may be formed as a result of aggregation of minuter lines of yielding which will be described later.

The investigation made by HARTMANN(29) shows that the special figures appear on the polished surface of circular metal plate which is supported on all the circumference of one face and subjected on the middle of the other face, to the action of a spherical stamp. These figures of deformation are composed of radiating straight lines and set of logarithmic spirals which assign the centre of plate as a pole. This pattern is known as HARTMANN's line produced on the surface of iron or steel plate by ball indentation. Recently Dr. NADAI(49)(50) has described the theory with respect to Hartmann's line.

Expecting that more or less regular pattern will be produced on the surface of wood by ball indentation, the present writer has made a microscopic observation with "Ultropak objective" on the ball impression produced on the end surface of wood.

Since the wood is not only very porous but also remarkably anisotropic in structure, it will be easily expected that the Hartmann's line produced in this way, may considerably differ from that of metal. In the present study, end surface of several wood species into which the steel ball had previously been pressed, were carefully examined, yet unfortunately, no regular pattern was found. Again in order to find this pattern, another species, Japanese box wood, the wood of the most uniform in texture, was also carefully examined, but almost similar result was obtained as in above case, although sometimes few irregular wavy lines across the ray were observed in the vicinity of the impression. As a rule, no regular pattern such as Hartmann's line of metals was found on the surface of wood.

## LINE OF FLOW IN THE INTERNAL REGION

It is very interesting to note the line of flow due to ball penetration which distributes in the internal region of wood. It is widely known that by etching the cut surface of metal with a certain reagent like a solution of cupric chloride in hydrochloric acid and water, it is possible to reveal the internal region which has previously been yielded and thus obtain information regarding the flow of metal at the points of stress concentration. The pattern produced in this way is known as etch-band.

In order to find the line of deformation corresponding to the etch-band of metal, the longitudinal section of wood cut through the center of the concaved surface of the ball impression was carefully examined and the lines somewhat analogous to the etch-band of metal were observed.

Within the injured region, these lines of yielding appear as stories of line which are more or less curved, running across the axes of fibers.

In the previous article, it has been described that the injured region in the cut surface may be readily distinguishable on account of the difference of luster. These area of dull luster consist of dense aggregation of Lueders' line.

The reason why the luster of injured region is dull compared with the uninjured portion surrounding it, may be explained as follows. Each fiber wall in the injured portion appears bruised and crinkled due to ball penetration, and the walls are so steeply inclined to the horizontal that light falling upon them, instead of reflected back into the lens of the microscope, is thrown out to the outside of lens. The fig. G will show this clearly.

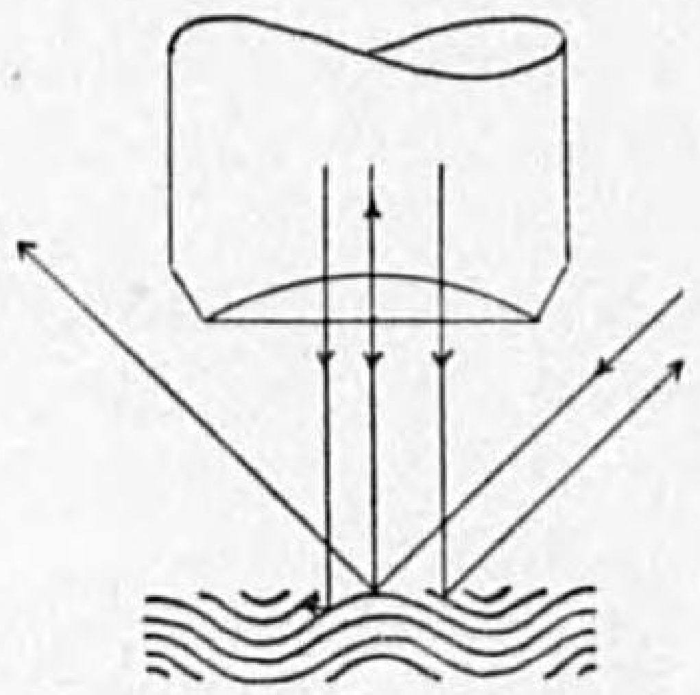

Fig. G.

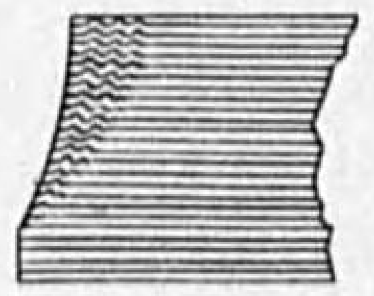

Fig. H.

The manner of aggregation of these lines of yielding will be seen more clearly when observed with a polarizing microscope. This laminar type of deformation is shown in fig. 20 which represents a section of *Kiri* photographed by polarized light. The observation shows the following facts as to the optical properties of these lines of yielding. When one of the axes of crossed Nicols is parallel or perpendicular to the longitudinal axis of fiber, uninjured portion in the field shows minimum luminosity or darkest and the zone of yielding clearly appears as bright zone against the dark back ground. When the axis of fiber is oriented at 45 degrees, the luminosity of the field, as a whole, maximum and the line of yielding in this case is scarcely distinguishable.

By careful observation, along the border of the injured part, the lines of yielding are often observed as more or less curved lines jut out from the injured area into the uninjured region surrounding it. This pattern appears to a certain degree to follow the mechanical theory discussed by **PRANDTL**(56) or **NADAI**(50).

In some woods such as *Kihada*, *Harigiri* and *Maguwa*, X-shaped lines were often observed in the vicinity of the injured part especially in the dense summer wood. According to G. **MESMER** (1930)(46), it was shown by means of mechanical as well as photo-elastic experiment that Lueders' lines produced by penetrating a bar, roller or cone into the mild steel almost coincide with the lines of principal shearing stress. J. **RATHYE** (1931)(57) observed the manner of displacement of the internal region by penetrating a bar into the sand pile and showed that the line of flow produced in this way more or less follows the mechanical theory.

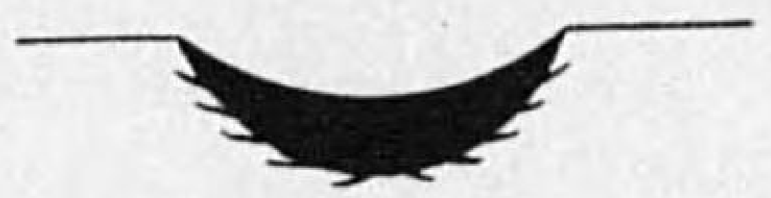

Fig. I.

The present writer also carried out somewhat analogous experiment as that of **RATHYE** using the clay as material to be tested, and more or less similar result was obtained. The pattern of flow obtained is shown in fig. 21.

Again, in order to observe the manner of localized stress, experiment was carried out by means of another method somewhat similar to so-called "Yield-point method". The surface of wood block to be tested was painted with a wash of white mortary fluid which will make brittle coating after dry. As load is applied, flaking off or cracking of the brittle coating gives a good indication of region of stress concentration. Fig. 22, shows the pattern produced in this way.*

Although wood is extremely heterogeneous in texture, the behavior of line of flow produced in internal region of wood by ball indentation has led to the idea that they may go in greater or less extent, parallel with the mechanical theory.

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* Stress distribution in this case will be shown by isochromatic lines which are given in Fig. 25. Since wood is not isotropic in structure these color bands does not show real distribution of stress in wood but they may serve to some extent as a reference.

## STAINING REACTION OF INJURED AREA

It has already been known that some kinds of stain and reagent indicate physical or mechanical change in the wall of wood fiber. Using chlor-zinc-iodide solution as staining reagent, ROBINSON(61) found that the zone of failure of wood due to compression or tension appears as blue band in contrast to the yellow stain given by the unaltered area and he explained this differential staining as follows.

Each particle of cellulose in the wall may be incrusted by a film of lignose substance which would lead the complete obscuring of particle of cellulose and would be incapable of forming normal cellulose reaction. When such film of lignose substance is split up by mechanical stress, cellulose would be revealed as a consequence. This would explain why the injured region holds the cellulose reaction whilst the uninjured part of the wall holds normal lignin reaction.

LÜDTKE, on the other hand, considered that each micella is encrusted by a film of unknown substance somewhat differ from lignin (*Fremdehaut*). And he contradicted the existence of lignose substance in the wall excepting middle lamella. He stated(40) that the typical color reaction of cellulose with chlor-zinc-iodide (violet) is decidedly negative only on the surface of cleavage of wall. In the cut- or broken surface, however, as in the injured area of carbohydrate lamella, the indication of this reaction will be recognized. Such reaction, therefore, will serve to identify the failure of wall as ROBINSON described.

Recently Dr. OHARA has made interesting researches by means of so-called "Metachromasie" on the submicroscopic structure of natural silk(54), various kinds of artificial silk(55) and cell wall of wood which had been buried more than 1,800 years(53). "Metachromasie" is understood to be special coloration which gives the different coloring for the different tissue by means of a certain single dye such as diamine green or oxamine blue*.

In accordance with A. CZAJA's investigation, Dr. OHARA described that this special coloration results from the difference of submicroscopic structure of tissue, in other words, such coloring matter gives the different coloration according to the degree of dispersion of the pigmentary particles in the intermicellular space. Dr. OHARA used oxamine blue 4R in his studies and obtained fair results.

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* Dr. OHARA says that E. FICHTE has ascertained that these two stains are particularly fitting for this purpose.

At any rate, the metachromatic coloration may be also serviceable to reveal the manner of localized injure in the wood tissue.

In order to reveal the manner of deformed area of internal region of wood due to ball indentation, the sections prepared from the wood block which had been indented were stained with several stains and reagents.

The effect of these are summarized in the following table.

TABLE III.

| Stain or Reagent. | Deformed area. | Unaltered area. |
|---|---|---|
| Aniline chloride followed by Aniline blue. | blue. | yellow. |
| Aniline chloride followed by Licht green. | bluish green. | greenish yellow. |
| Aniline sulphate followed by Aniline blue. | blue. | yellow. |
| Aniline sulphate followed by Eosin bluish. | orange. | yellow. |
| Aniline sulphate followed by Licht green. | bluish green. | greenish yellow. |
| Benzidine | lemon yellow. | lemon yellow. |
| Benzine & $H_2SO_4$ | reddish orange. | reddish orange. |
| Benzidine followed by Aniline blue. | green. | yellow. |
| Benzidine followed by Licht green. | green. | yellow. |
| Bismark brown followed by Aniline blue. | blue. | brownish green. |
| Chlor-zinc-iodide. | blue. | yellow. |
| Congo red followed by Aniline blue. | brownish purple. | violet. |
| Congo red followed by Aniline chloride. | brownish red. | orange. |
| Congo red followed by Aniline sulphate. | brownish red. | reddish orange. |
| Congo red followed by Malachite green. | indigo blue or dark violet. | green. |

TABLE III. (*Continued*)

| Stain or Reagent. | Deformed area. | Unaltered area. |
|---|---|---|
| Congo red & $H_2SO_4$ | dark blue. | violet. |
| Diamidophenol | reddish orange or brownish red. | reddish orange or brownish red. |
| Diamidophenol & HCl (or $H_2SO_4$) | yellow. | yellow. |
| Diamidophenol followed by Aniline blue. | blue. | purple. |
| Diamidophenol followed by Licht green. | green. | reddish brown. |
| Diphenylamine & HCl | yellow to orange. | yellow to orange. |
| Eosin bluish followed by Licht green. | bluish green. | bluish violet. |
| Eosin yellowish followed by Aniline blue. | violet. | crimson. |
| Eosin yellowish followed by Malachite green. | green. | violet. |
| Haematoxylin & HCl (or $H_2SO_4$) | crimson. | crimson. |
| Iodine & Licht green | green. | yellow. |
| Malachite green followed by Aniline chloride. | yellow. | green. |
| Malachite green followed by Aniline sulphate. | yellow. | green. |
| Naphtylamine & HCl | orange. | orange. |
| Oxamine blue 4R. | blue. | violet. |
| Phenylendiamine hydrochlorate | blick red. | blick red. |
| Phenylendiamine hydrochlorate followed by Aniline blue. | blue. | yellowish brown. |
| Phenylendiamine hydrochlorate followed by Licht green. | green. | orange. |
| Phloroglucinol & HCl | cherry red. | cherry red. |
| Potassium iodide & $H_2SO_4$ | yellow. | yellow. |
| Resorcinol & $H_2SO_4$ (or HCl) | violet. | violet. |

TABLE III. (*Continued*)

| Stain or Reagent. | Deformed area. | Unaltered area. |
|---|---|---|
| Safranin followed by Aniline blue. | blue. | red. |
| Safranin followed by Haematoxylin. | blue. | red. |
| Safranin followed by Licht green. | bluish green. | purplish red. |
| Safranin followed by Malachite green. | dark green. | reddish violet. |
| Safranin & $H_2SO_4$ | purple. | purple. |
| *p*-Toluidine & HCl | lemon yellow. | lemon yellow. |

## SLIP LINE OF THE FIBER WALL

In the previous articles, some results of partly macroscopic and partly microscopic observation were described in regard to the deformation of wood block which had previously been indented with a steel ball. In this article, more advanced observation will be made especially in connection with the failure of fiber wall.

ROBINSON(61) recognized that minuter change takes place preceeding the buckling or crinkling of the wall of wood element, when wood block is subjected to stress. He stated it as the change that leads to deformation and consists in appearance of extremely fine but sharply defined crack-like line in the wall of tracheid to which he gave the name of "slip line" or "slip plane". According to his description, the slip lines or planes present certain similarities to the slip bands or gliding planes described by EWING and ROSENHAIN for the crystals of materials under strain, and by REUSCH and others at an earlier period for many crystalline substances.

According to ROSENHAIN(62), the origin of the slip-bands of metal lies in the fact that when a crystal of a ductile material is forciably altered in shape, it adapts itself to the new configuration imposed upon it by a process of sliding or slip which occurs on certain of its crystallographic plane. The manner in which this occurs is well illustrated by the behavior of a pack of cards, or of a pile of books, when the pile is distorted—the shape of each individual card or book remains unchanged but the shape of the pile is changed by sliding of the individual cards or books over one another.

The slip line defined by ROBINSON for the element of wood under strain, however, may not be essentially equal to the slip band or *Gleitlinie* of ordinary crystalline materials, although wall of wood element is generally considered as ultra-micro-crystalline texture. Since the time of NÄGELI, the rightness of micellular theory has been proved by many investigators, and it may be natural to consider that slips would take place along the crystallographic plane of the infinitesimal unit by means of applied pressure. It is obvious, however, that the slip line defined by ROBINSON does not mean such ultramicroscopic slipping, but grosser line which is recognized as bright line under polarizing microscope. This line or plane may be considered as such line or plane which bears some resemblance to so-called *Verschiebungslinie* resulting from swerving of micellae.

These phenomena or so-called *Verschiebungen* have previously been studied in many herbaceous fibers by Dr. von HÖHNEL (32) and he concluded that the simple cross lines and folds result from inequalities of the radial pressure of the tissues in the plant, and are therefore of physiological origin. Dr. SCHWENDENER (1894) (63) also made a study on the *Verschiebungen*, but on the contrary, he considered them as resulting from artificial influences during the process of preparation, since in fibers which are obtained by simple rotting in water such distortions are either completely lacking or are sparingly present and but feebly developed.

Dr. HANAUSEK (1901) (25) also recognized these cross-lines or cross-folds in the wall of fiber. He stated that in worn out linen thread or fabrics, these characteristics are so marked that the wall appears distinctly striated, bruised, much broadened, with tumorlike swelling, all of which doubtlessly result from the treatment of the raw material. In disorganized fibers of some textile materials* such as flax, hemp, ramie etc., he observed discoloration or folds resulting from compression, also swelling and cross-fissures as described above.

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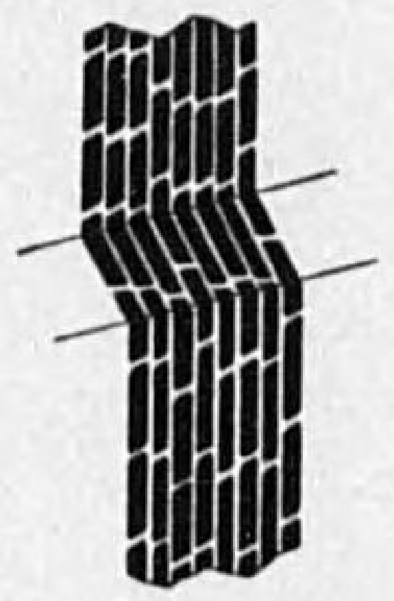
* He described that in jute bruises and discoloration are not present, their absence being probably connected in some way with the absence of laminations.

Dr. JACCARD (1910) (34) also noticed some platings (*Plissements*) or foldings in the wall of trachid of Pinus silvestris. He stated that these plaitings of wall which are usual in coniferous wood but less frequent in broad leaved species, often produce the little transverse fissures in more or less equidistance in the wall of fiber and that these lines are absolutely comparable to those of the figure in v. HÖHNEL's work.

Dr. H. AMBRONN (1925) (2) also recognized *Verschiebungslinie* in cellulose fiber, bast fiber, *Faden* or cellulose filament such as epidermic filament of Cobaea or Rosenbergia seed etc., and he considered it just the same as gliding line which is produced in real crystalline materials*. Basing upon this idea, he made further arguments for crystalline structure of cellulose.

In the *Verschiebungslinie*, as shown by optic properties, the micellae are oriented to the longitudinal axis of fiber in short distance inclining at some legal angle (see fig. J.)

This is considered to be more or less similar to a process of plastic deformation of crystal well known as *einfache Schiebung* defined by REUSCH.



Schematic representation of "einfache Schiebung".

Fig. J.

As has already been described, many reliable proofs for rightness of NAGELI's micellular theory has been made, although earlier explanation of this theory is modified in some degree by the modern advanced investigators. From this idea it might be natural to assume that the infinitesimal slippings—*Translation* or *Schiebung*—would take place along a certain plane in a micella by means of ball indentation.

Both of two observations, one by ROBINSON and the other by JACCARD were principally made in regard to the failure due to end compression of wood. But it will be easily expected that in the case of ball indentation test of wood, so-called slip lines may be also produced. In fact, the present writer observed numerous slip lines in the fiber wall of wood which had previously been subjected to ball

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*Dr. FREY-WYSSLING considers that *Gleitfläche* and *Verschiebungslinie* are not identical (20).

indentation. These lines were recognized in the wall of spring wood fiber as well as summer wood fiber of both coniferous and broad leaved species.

It was observed that each slip line usually appears as a line extending across the wall at the angle of 45°–70° with the longitudinal axis of fiber, although sometimes it appears almost horizontally. The slopes of these bands may be either direction and often form cross hatching. When the microscopic section prepared from wood block which has previously been indented with a steel ball, is observed under crossed Nicols, the slip lines can much more easily be recognized as bright lines extending across the wall of fiber. Fig. 27–28 represent these slip lines which appeared in the wall of fiber due to ball indentation.

Since the discovery by LAUE, BRAGG and others of the interference of X-rays, many substances whose crystalline nature was not previously known, have been found to be micro- or cryptocrystalline; for instance some characteristics of micellae whose nature is beyond the resolving power of microscope have been shown by X-ray research*. These crystalline units which possess any sort of regularity present us with problems of bringing their mechanical properties into connection with the special character of this regularity or texture.

Anyhow, it may be natural to consider that such ultra-microscopic slippings in a micella gradually increase in number with the strain, becoming closer together and at the same time swerving or confusion of arrangement of micellae may take place and finally there occurs minute change or flow in the wall which is visible as bright line under the polarizing microscope. This is considered to be the line that ROBINSON named the slip line of fiber wall.

This gliding process, however, might be complicated and more or less analogous to so-called "Flexture gliding" which is neither pure *Translation* nor *einfache Schiebung*. Though it is known that the idea of flexure gliding was applied to crystalline materials under tension by MÜGGE and POLANYI, it might be applicable in greater or less degree to the case of deformation of micellular constitution under

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* It is well known that the fundamental knowledge in regard to submicroscopic structure of lignified membrane was obtained by Dr. HERZOG by means of X-ray investigation.

ball indentation. Anyhow, this is only analogical construction and there is little direct evidence for this, hence the further investigation will be necessary to solve such a problem as flexure gliding of micellae.

These slip lines which are visible under polarized light increase in number with the strain until at last the group of these lines bring about grosser localized flow of wood tissue forming the line of deformation along the direction of maximum strain. These grosser lines of deformation which are often visible by unaided eye, will form the special pattern known as Lueders' line or Hartmann's line.

ROBINSON noticed that the direction of line is common to the secondary layers of pair of walls of adjoining tracheids but no line has been observed crossing the middle lamella between adjoining tracheids and he stated that this probably signifies a difference in the elastic properties of middle lamella. The similar manner was also observed in the case of ball indentation.

The reason why no slip line crosses through the middle lamella may be considered as follows. The middle lamella, the isotropic peripheral layer of the cell wall, is not doubly refractive and is supposed to exist in somewhat amorphous condition. Since the atoms of amorphous materials do not occupy fixed position with respect to one another, such materials can be deformed by gradual shifting of the relative positions of their particles. The atoms in a crystalline material are held in substantially fixed positions in crystal lattice. Deformation therefore takes place by the simultaneous movement of a large number of atoms. In contrust to crystal, the cohesion bonds in an amorphous material may be broken very gradually—more or less similar to that which is supposed to exist in somewhat liquid state, consequently it may show no abrupt change which occurs in crystalline substance.

It is considered that the formation of slip lines marks the beginning of deformation and therefore the passing of the elastic limit. The resistance to parmanent deformation, which is a general measure of mechanical properties of material, represents resistance to the beginning and propagation of slip. Anything that serves to hinder slip is a source of strength and hardness.

It is generally considered that the pits in the wall of tracheid or fiber form points of weakness. In the anatomical study of compression failure of wood, JACCARD(34) stated that the plaiting of tracheid corresponds to the pit which forms the point of less resistance in the wall, and along the line of the plaiting the pit is more or less crushed or simply deformed. But BIENFAIT(8) stated that photomicrographs made for the study of initial failures show that evidence for supporting such a relation is lacking, and the argument therefore fails as an explanation of the character or the commencement of the failure.

Regarding to the failure due to end compression of wood, FORSAITH(16) recognized that the wall between the pits (especially on the outer margin of the pit flange) is more inclined to collapse than is the pit to close at the orifice.

In the present stduy, careful observation was made with respect to such manner of failure as described above, but no sufficient conclusion was obtained although in some occasions pits crushed more or less along the line of buckling were found.

In the study of submicroscopic structure of cell wall, FREY-WYSSLING(17)(21) showed that micellae in the wall of tracheid or vessel are arranged in spiral order, while in the pit they are arranged in remarkably circular order.

When the pits of tracheid wall are observed under crossed Nicols, dark lines forming a cross in the circular flange of pit will be recognized. These dark crossed lines always coincide with the axes of crossed Nicols irrespective of the direction of fiber, in other words, the direction of these lines are invariable by rotating the stage of microscope carrying the section. Fig. 31 and 32 represent the walls of tracheid at the position of extinction and those at the position of rotating 45° from extinction respectively.

Owing to such marked difference of arrangement of micellae, it is very natural to consider that the pit in the wall is closely related with the commencement of failure.

Slip lines are much more numerous in the cell wall of the region deformed due to ball indentation. These lines are always found in woods subjected to stress and very often found even in the wood not previously subjected to any mechanical testing. In the latter case, as usually considered, they may be due to stresses resulting from the weight of tree, wind action, rough handling etc.

The weight of tree and the wind action, besides some other actions, are usually mentioned as the causes of compressive wood formation. In order to find any existence of slip line in the fiber wall, microscopic observation was made on a number of sections prepared from compressive wood of *Hinoki*. But unfortunately, no such line was found in the present study. Although this observation does not show absolute lacking of slip line in the wall of element of compressive wood, it will be at least shown that slip lines do not always exist in the wall of such element.

It was considered that the existence of so-called spiral cracking of the wall of wood element might affect in more or less extent the elastic properties of wood, consequently the wall which contains the spiral crackings is supposed to be more liable to produce slip line. In order to ascertain this fact, observations were made on a number of sections prepared from *Akamatsu*, *Togasawara*, *Aka-ezomatsu*, *Shonanboku* which usually contain many spiral crackings.

But no slip line was found in almost all sections examined, and no special relation was found between the existence of slip line and spiral cracking.

## RELATION OF THE DEPTH OF INDENTATION TO THE APPLIED LOAD

It is a matter of course that the depth of the ball indentation is increased by increasing the load to be applied. In order to find the relation of the depth of indentation to the corresponding applied load, a series of experiments was carried out as follows. A steel ball of 10 mm. diameter was pressed into the end surface of wood including 12 species, and the depth of ball indentation was noted in every 25 kg. of applied load.

The materials were tested in air dry condition. The average depth to the corresponding applied load and the hardness number calculated are shown in Table IV and the curves which represent the relation of the depth to the applied load in each species are shown in fig. K and L. Each point in the diagrams was obtained from the average of 40 impressions.

It is found that within a certain limit, the relation of $h$ to $P$ is represented by the following equation with considerable accuracy.

$$P = ah^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

TABLE IV.

i. *Shirakashi.*

| Load (kg.) | depth | $H_B$ | $H_M$ |
|---|---|---|---|
| 25 | 3.62 | 21.928 | 22.062 |
| 50 | 9.77 | 16.289 | 16.450 |
| 75 | 16.57 | 14.407 | 14.650 |
| 100 | 23.80 | 13.374 | 13.700 |
| 125 | 31.62 | 12.583 | 12.994 |
| 150 | 39.47 | 12.096 | 12.593 |
| 175 | 48.62 | 11.457 | 12.042 |
| 200 | 59.02 | 10.786 | 11.462 |
| 225 | 68.62 | 10.447 | 11.206 |
| 250 | 78.67 | 10.115 | 10.979 |
| 275 | 89.52 | 9.778 | 10.739 |
| 300 | 100.45 | 9.506 | 10.567 |
| 325 | 111.45 | 9.282 | 10.446 |
| 350 | 123.67 | 9.008 | 10.279 |
| 375 | 137.20 | 8.700 | 10.083 |

ii. *Keyaki.*

| | | | |
|---|---|---|---|
| 25 | 6.15 | 12.939 | 13.019 |
| 50 | 16.12 | 9.872 | 10.034 |
| 75 | 25.42 | 9.391 | 9.636 |
| 100 | 34.75 | 9.160 | 9.490 |
| 125 | 44.25 | 8.992 | 9.408 |
| 150 | 54.10 | 8.826 | 9.330 |
| 175 | 64.50 | 8.636 | 9.232 |
| 200 | 77.35 | 8.230 | 8.920 |
| 225 | 88.97 | 8.050 | 8.836 |
| 250 | 101.47 | 7.842 | 8.728 |
| 275 | 115.05 | 7.608 | 8.598 |
| 300 | 129.17 | 7.393 | 8.489 |
| 325 | 144.20 | 7.174 | 8.383 |

TABLE IV. *(Continued)*

iii. *Nara.*

| Load (kg.) | depth | $H_B$ | $H_M$ |
|---|---|---|---|
| 25 | 5.10 | 15.603 | 15.683 |
| 50 | 13.75 | 11.574 | 11.736 |
| 75 | 23 12 | 10.325 | 10.570 |
| 100 | 33.42 | 9.525 | 9.854 |
| 125 | 44.90 | 8.862 | 9.278 |
| 150 | 56.50 | 8.451 | 8.957 |
| 175 | 68.67 | 8.112 | 8.710 |
| 200 | 83.85 | 7.592 | 8.287 |
| 225 | 99.30 | 7.212 | 8.007 |
| 250 | 114.67 | 6.940 | 7.839 |
| 275 | 131.77 | 6.643 | 7.651 |
| 300 | 148.75 | 6.420 | 7.542 |
| 325 | 167.07 | 6.192 | 7.434 |

iv. *Kuri.*

| | | | |
|---|---|---|---|
| 25 | 6.55 | 11.966 | 12.046 |
| 50 | 15.25 | 10.436 | 10.597 |
| 75 | 24.40 | 9.784 | 10.028 |
| 100 | 34.20 | 9.307 | 9.637 |
| 125 | 46.80 | 8.502 | 8.919 |
| 150 | 58.60 | 8.148 | 8.655 |
| 175 | 70.25 | 7.929 | 8.529 |
| 200 | 86.02 | 7.401 | 8.097 |
| 225 | 101.12 | 7.083 | 7.879 |
| 250 | 116.60 | 6.825 | 7.726 |
| 275 | 134.27 | 6.519 | 7.531 |

v. *Harigiri.*

| | | | |
|---|---|---|---|
| 25 | 10.90 | 7.301 | 7.381 |
| 50 | 23.67 | 6.724 | 6.887 |
| 75 | 40.00 | 5.968 | 6.217 |
| 100 | 58.80 | 5.413 | 5.753 |
| 125 | 78.12 | 5.093 | 5.525 |

TABLE IV. (*Continued*)

| Load (kg.) | depth | $H_B$ | $H_M$ |
|---|---|---|---|
| v. *Harigiri.* | | | |
| 150 | 95.00 | 5.026 | 5.553 |
| 175 | 118.52 | 4.700 | 5.332 |
| 200 | 146.72 | 4.339 | 5.085 |
| 225 | 175.72 | 4.076 | 4.945 |
| vi. *Katsura.* | | | |
| 25 | 11.35 | 7.011 | 7.092 |
| 50 | 23.62 | 6.738 | 6.901 |
| 75 | 36.70 | 6.505 | 6.753 |
| 100 | 54.37 | 5.855 | 6.191 |
| 125 | 72.12 | 5.517 | 5.946 |
| 150 | 91.05 | 5.244 | 5.769 |
| 175 | 112.12 | 4.968 | 5.596 |
| 200 | 138 65 | 4.592 | 5.331 |
| 225 | 166.17 | 4.310 | 5.168 |
| vii. *Kihada.* | | | |
| 25 | 13.17 | 6.042 | 6.123 |
| 50 | 27.72 | 5.741 | 5.905 |
| 75 | 42.70 | 5.591 | 5.840 |
| 100 | 60.90 | 5.227 | 5.566 |
| 125 | 81.70 | 4.870 | 5.303 |
| 150 | 102.90 | 4.640 | 5.172 |
| 175 | 128.02 | 4.351 | 4.990 |
| viii. *Hohnoki.* | | | |
| 25 | 13.40 | 5.939 | 6.019 |
| 50 | 28.45 | 5.594 | 5.758 |
| 75 | 43.33 | 5.510 | 5.759 |
| 100 | 58.10 | 5.480 | 5.817 |
| 125 | 77.70 | 5.121 | 5.552 |
| 150 | 102.80 | 4.645 | 5.177 |
| 175 | 132.47 | 4.205 | 4.847 |

TABLE IV. (*Continued*)

| Load (kg.) | depth | $H_B$ | $H_M$ |
|---|---|---|---|
| ix. *Tsuga.* | | | |
| 25 | 6.80 | 11.702 | 11.782 |
| 50 | 15.12 | 10.525 | 10.687 |
| 75 | 23.75 | 10.051 | 10.296 |
| 100 | 32.57 | 9.773 | 10.102 |
| 125 | 43.27 | 9.196 | 9.611 |
| 150 | 54.47 | 8.766 | 9.271 |
| 175 | 66.90 | 8.326 | 8.923 |
| 200 | 81.90 | 7.773 | 8.467 |
| 225 | 96.57 | 7.416 | 8.209 |
| 250 | 112.52 | 7.072 | 7.969 |
| 275 | 127.95 | 6.841 | 7.845 |
| x. *Hinoki.* | | | |
| 25 | 8.37 | 9.507 | 9.588 |
| 50 | 18.57 | 8.570 | 8.733 |
| 75 | 30.52 | 7.822 | 8.068 |
| 100 | 44.60 | 7.137 | 7.470 |
| 125 | 60.52 | 6.575 | 6.998 |
| 150 | 75.82 | 6.297 | 6.814 |
| 175 | 92.37 | 6.031 | 6.644 |
| 200 | 114.22 | 5.574 | 6.293 |
| 225 | 135.32 | 5.293 | 6.121 |
| 250 | 158.17 | 5.031 | 5.976 |
| xi. *Himeko-matsu.* | | | |
| 25 | 11.17 | 7.124 | 7.205 |
| 50 | 24.97 | 6.374 | 6.537 |
| 75 | 42.82 | 5.575 | 5.825 |
| 100 | 68.10 | 4.674 | 5.016 |
| 125 | 102.35 | 3.888 | 4.307 |
| 150 | 143.70 | 3.323 | 3.880 |

TABLE IV. (*Continued*)

xii. *Sugi.*

| Load (kg.) | depth | $H_B$ | $H_M$ |
|---|---|---|---|
| 25 | 18.92 | 4.206 | 4.287 |
| 50 | 39.95 | 3.984 | 4.150 |
| 75 | 63.85 | 3.739 | 3.994 |
| 100 | 92.50 | 3.441 | 3.792 |
| 125 | 133.70 | 2.976 | 3.435 |

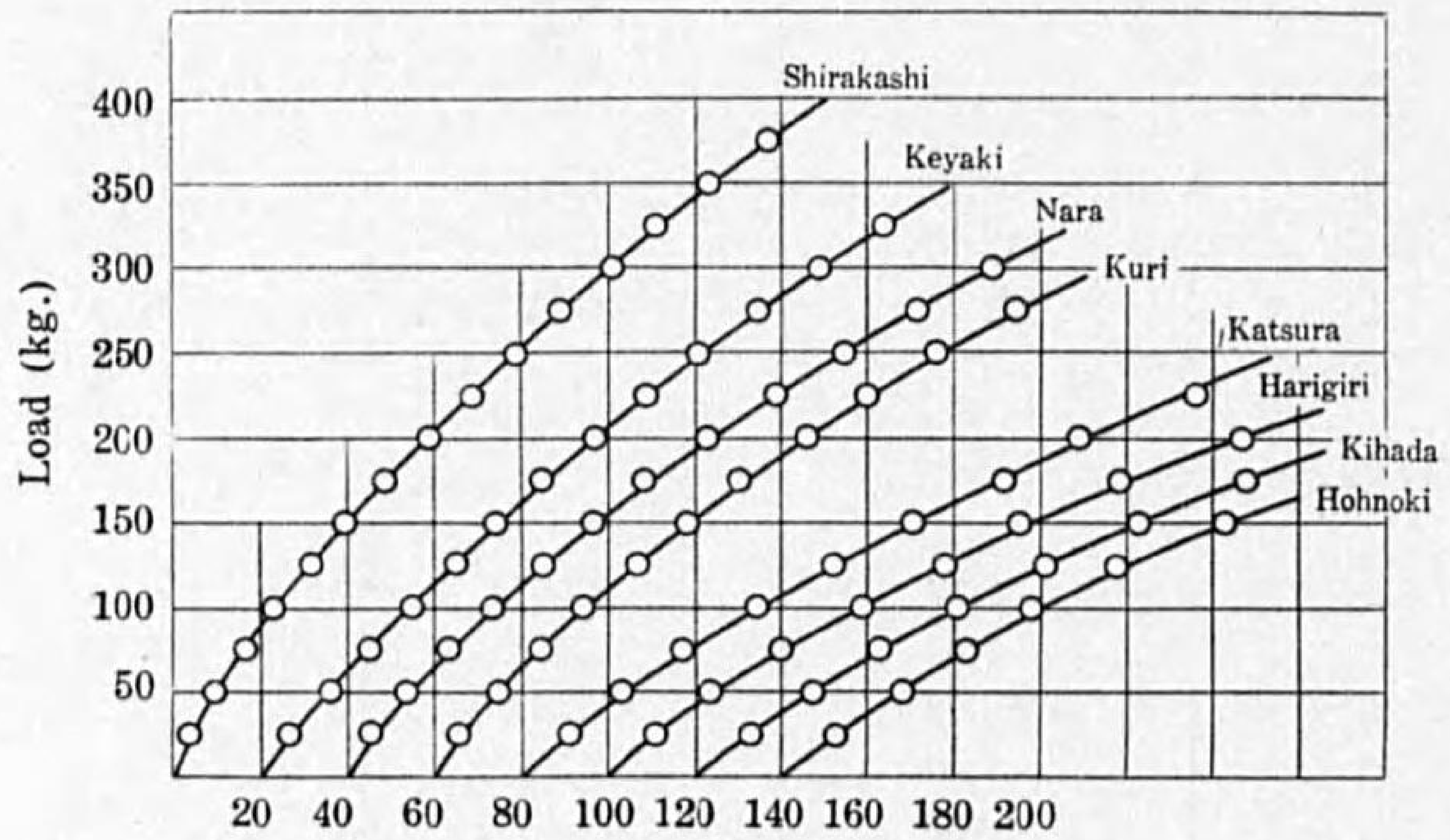


Fig. K.

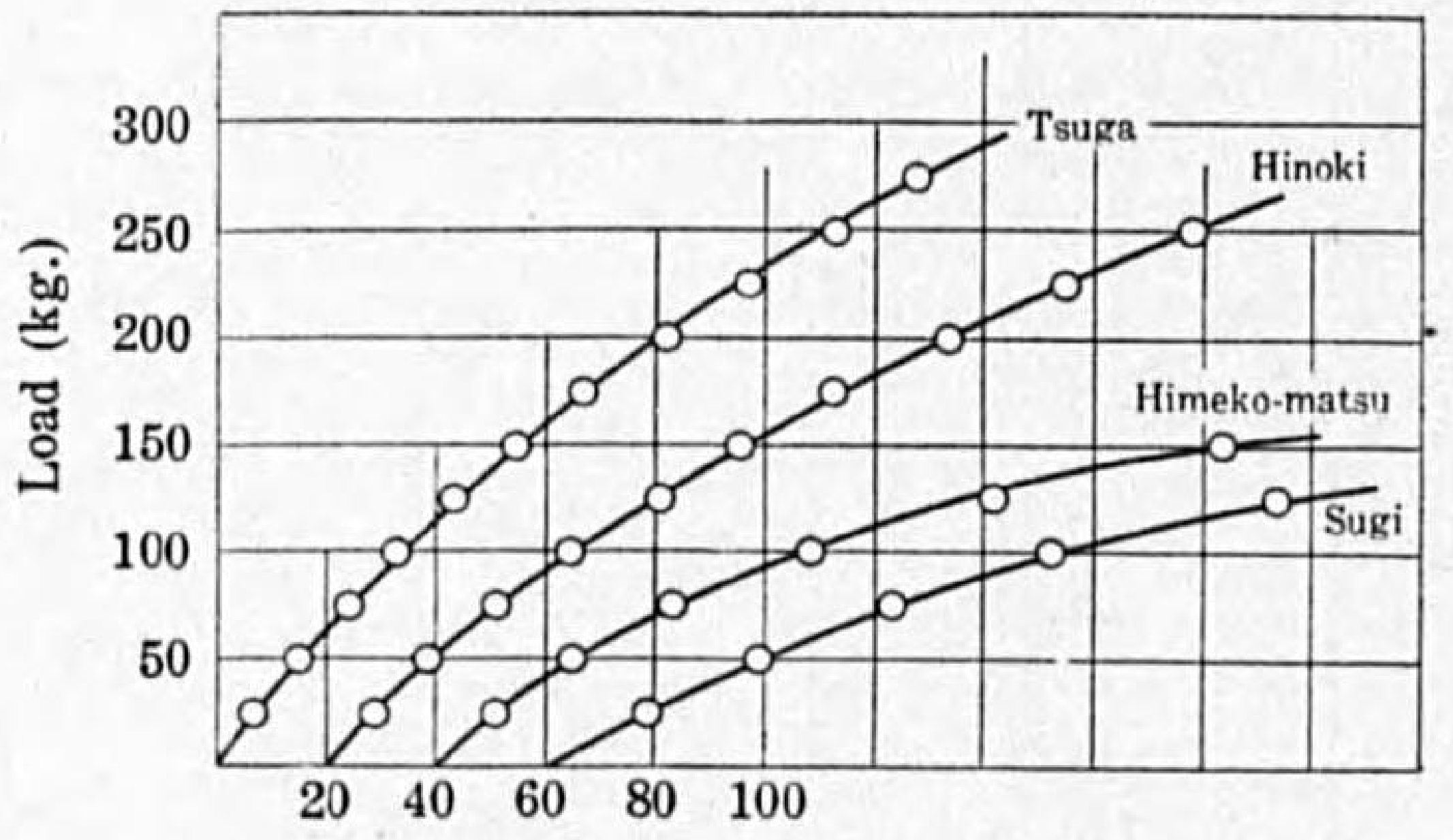


Fig. L.

where $P$ is the load in kg., $h$ is the depth of indentation (in mm. $\times 10^{-2}$), $a$ and $n$ are constants depending upon a given material and a given ball diameter.

The values of constants $a$ and $n$ in each species were determined from the data by means of calculation (least square) and the equations which represent load-depth relation for the species tested were obtained as follows:

TABLE V.

| | |
|---|---|
| 1. *Shirokashi* | $P = 9.200\ h^{0.755}$ |
| 2. *Keyaki* | $P = 5.232\ h^{0.835}$ |
| 3. *Nara* | $P = 7.349\ h^{0.744}$ |
| 4. *Kuri* | $P = 5.732\ h^{0.798}$ |
| 5. *Harigir* | $P = 3.981\ h^{0.790}$ |
| 6. *Katsura* | $P = 3.749\ h^{0.813}$ |
| 7. *Kihada* | $P = 2.869\ h^{0.856}$ |
| 8. *Honoki* | $P = 3.155\ h^{0.828}$ |
| 9. *Tsuga* | $P = 5.552\ h^{0.815}$ |
| 10. *Hinoki* | $P = 5.203\ h^{0.770}$ |
| 11. *Himeko-matsu* | $P = 4.466\ h^{0.729}$ |
| 12. *Sugi* | $P = 2.251\ h^{0.833}$ |

It is noticeable that the values of $n$ thus calculated are always less than unity—($0.7 \sim 0.9$)—within the range of the present investigation.

Observation shows that in ball indentation test, when a load is applied the specimen does not produce the complete indentation immediately. There is a certain creep that is, under a certain load, the specimen continues to give way slowly for a certain length of time. This time effect depends on the species or structure of wood and on the magnitude of the stresses involved. Loaded within a certain limit, this time effect is almost negligible but when loaded beyond the limit, the creeping increases gradually with increasing of load.

Within a species, the load under which the creeping is recognized seems to be confined within a certain range. It was observed that such loads as above in hard wood species were somewhat higher than those in soft wood species. For instance, within the range of this study, "creep" generally began to appear at the load about 100～175 kg. in hard wood species, and about 75～125 kg. in soft wood species. The load and the corresponding depth under which the beginning of creep were recognized may be approximately estimated as follows:

TABLE VI.

| | load (kg.) | depth (mm. × $10^{-2}$). |
|---|---|---|
| *Shirakashi* | 150–175 | 40–50 |
| *Keyaki* | 150–175 | 50–60 |
| *Nara* | 125–150 | 40–60 |
| *Kuri* | 100–125 | about 40 |
| *Harigiri* | about 100 | 40–50 |
| *Katsura* | 100–125 | 50–60 |
| *Kihada* | about 100 | about 50 |
| *Honoki* | about 100 | 40–50 |
| *Tsuga* | 100–125 | 40–50 |
| *Hinoki* | 100–125 | about 40 |
| *Himeko-matsu* | about 100 | 40–50 |

The time during which the pressure is applied is very important. Consequently the following notation may be used in specification of the ball indentation hardness.

$$H_{(D/P/S)},$$

where $H$ represents hardness number, $D$ diameter of ball in mm., $P$ applied load in kg., and $s$ time in second during which the load is applied. For instance, when the test is made with a 20 mm. diameter ball and a load of 500 kg. which is maintained for 30 seconds, Brinell's number obtained will be represented by

$$H_{B(20/500/30)}$$

In the present study, it is found that the time effect is most marked up to about 30 seconds' application of the load, but after about 30 seconds the effect is very small.

It is of course necessary that prior to testing, the surface of sample shall be clearly planed at the point to be tested.

In the case of homogeneous material, small load and small indentation are evidently being more preferred in the testing to large load and to large indentation, in wood which is very heterogeneous in texture, however, in choosing the place on the block for the indentation, effort should be made to get a fair average of fine and coarse grain or early and late wood. For this purpose, it may be convenient to use 20 mm. diameter ball instead of 10 mm. diameter ball which is generally used in the indentation test of materials.

## THE LOAD-HARDNESS CURVE

The hardness number defined by BRINELL or MEYER is represented by the mean pressure per unit spherical or projected area of the ball impression respectively. But since the load-depth curve ($P$–$h$ curve) is represented by the equation $P = ah^n$, it is evident that hardness numbers obtained by means of different applied loads are not comparable with each other. The comparison tests, therefore, should be made under the same weight of load; but different weight of load may be employed, provided that all results are reduced to a standard by means of a certain calculation.

The relation between the load and the hardness number for each species tested may be derived from the data of Table IV. These load-hardness curves are shown in fig. M～P. From these curves, it may be easily understood that for the strictly comparable results, fixed value must be used for the load $P$.

As shown in fig. M～P, MEYER's hardness number is always greater than BRINELL's number for the same material, when used the same size of ball and the same load. This relation may be also shown as follows:

$$H_B = \frac{P}{\pi Dh}, \qquad H_M = \frac{P}{\pi (d^2/4)},$$

where $P$ = load, $D$ = diameter of ball, $h$ = depth of indentation, $d$ = diameter of impression, and $H_B$ and $H_M$ are BRINELL's and MEYER's number respectively.

Since $d^2/4 = h(D-h)$,

for the same impression,

$$H_B/H_M = 1-h^{\cdot}/D$$

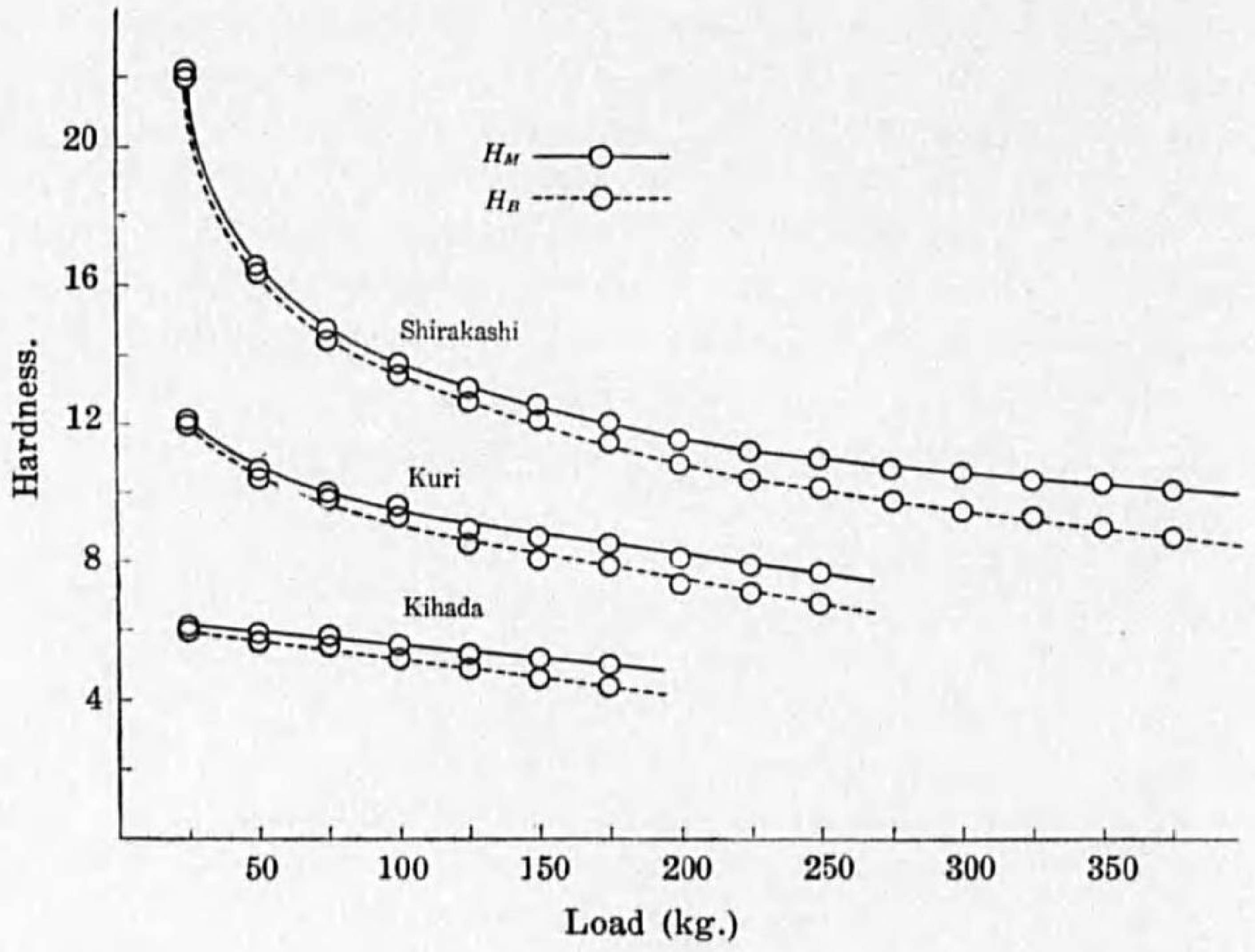


Fig. M.

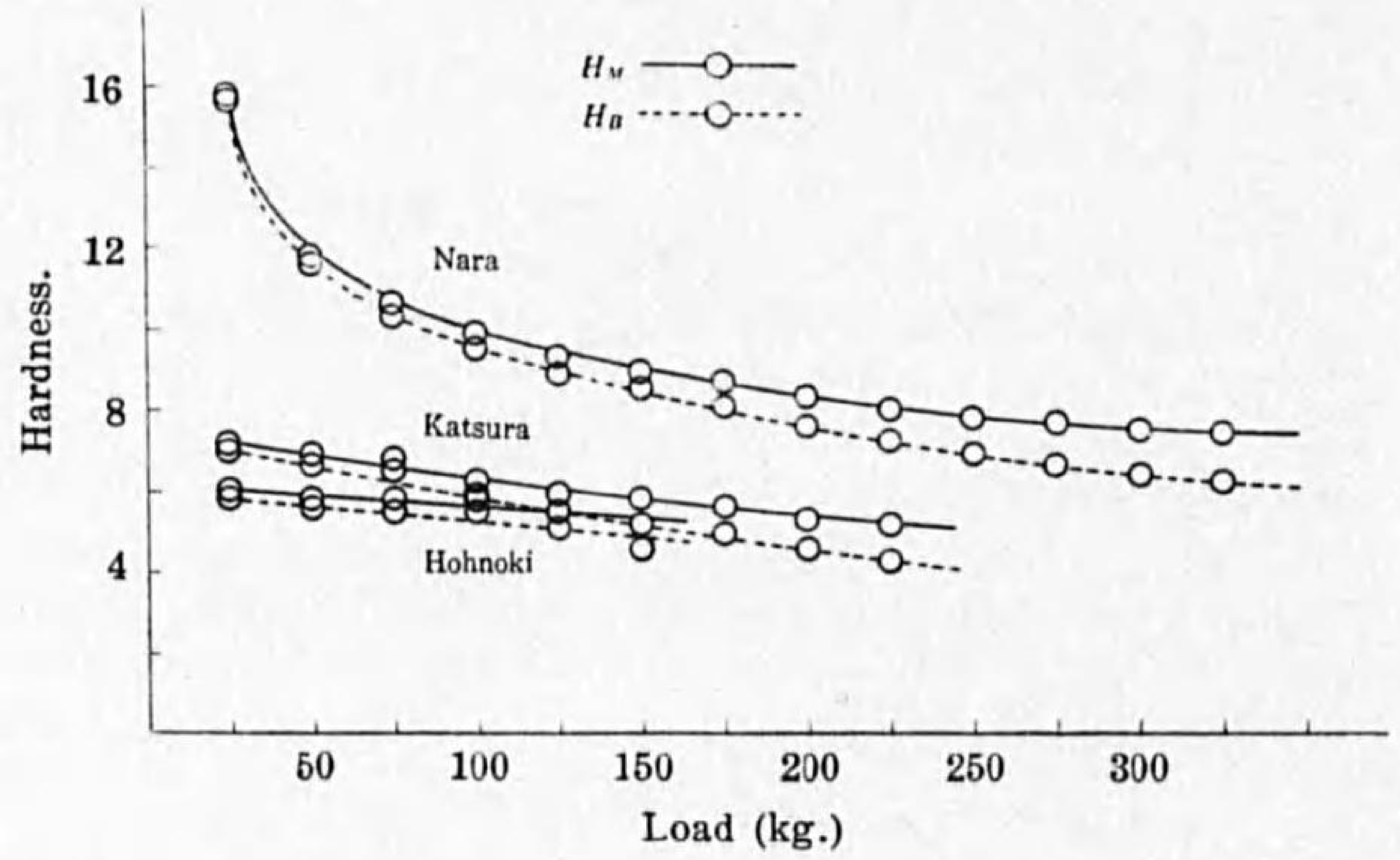


Fig. N.

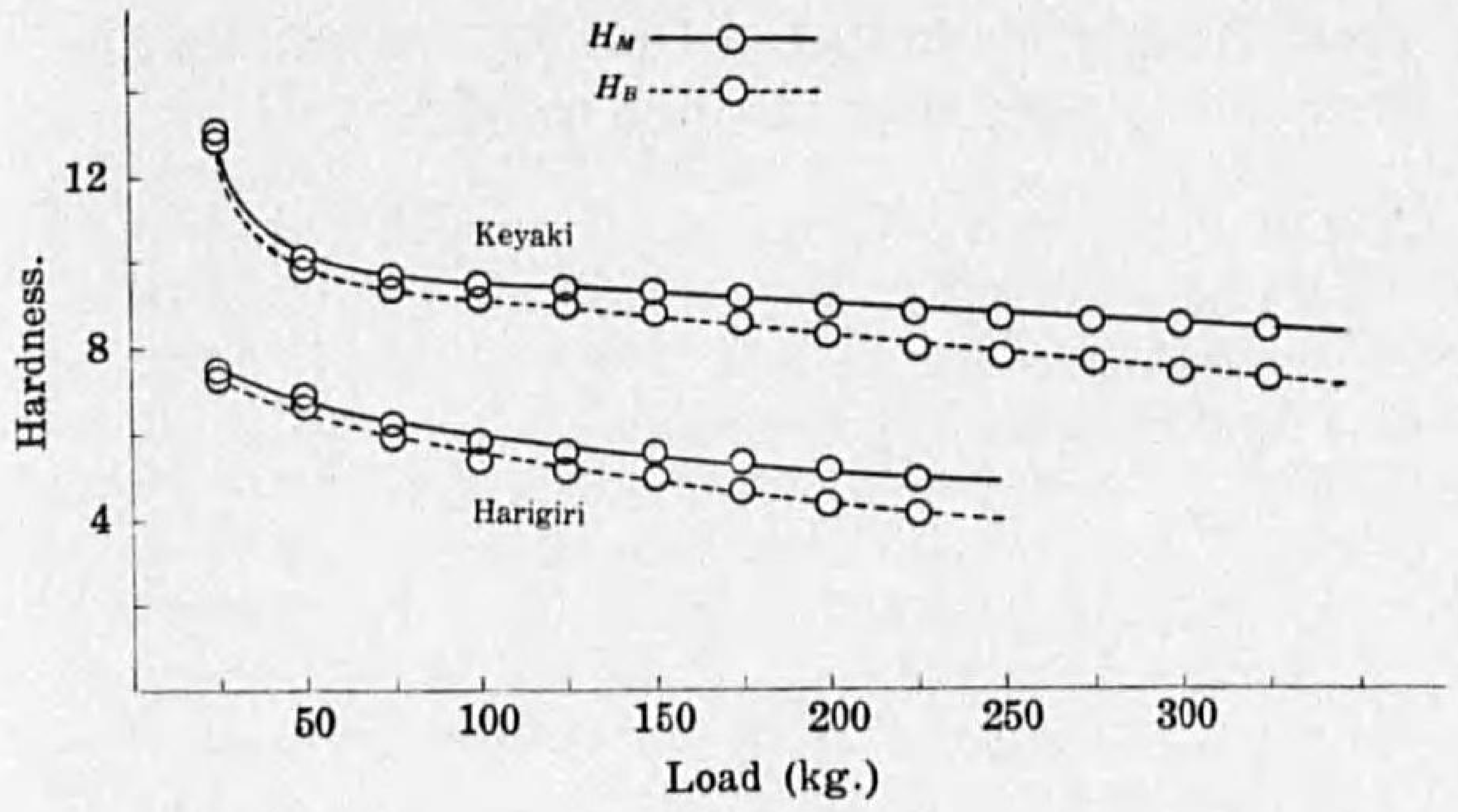


Fig. O.

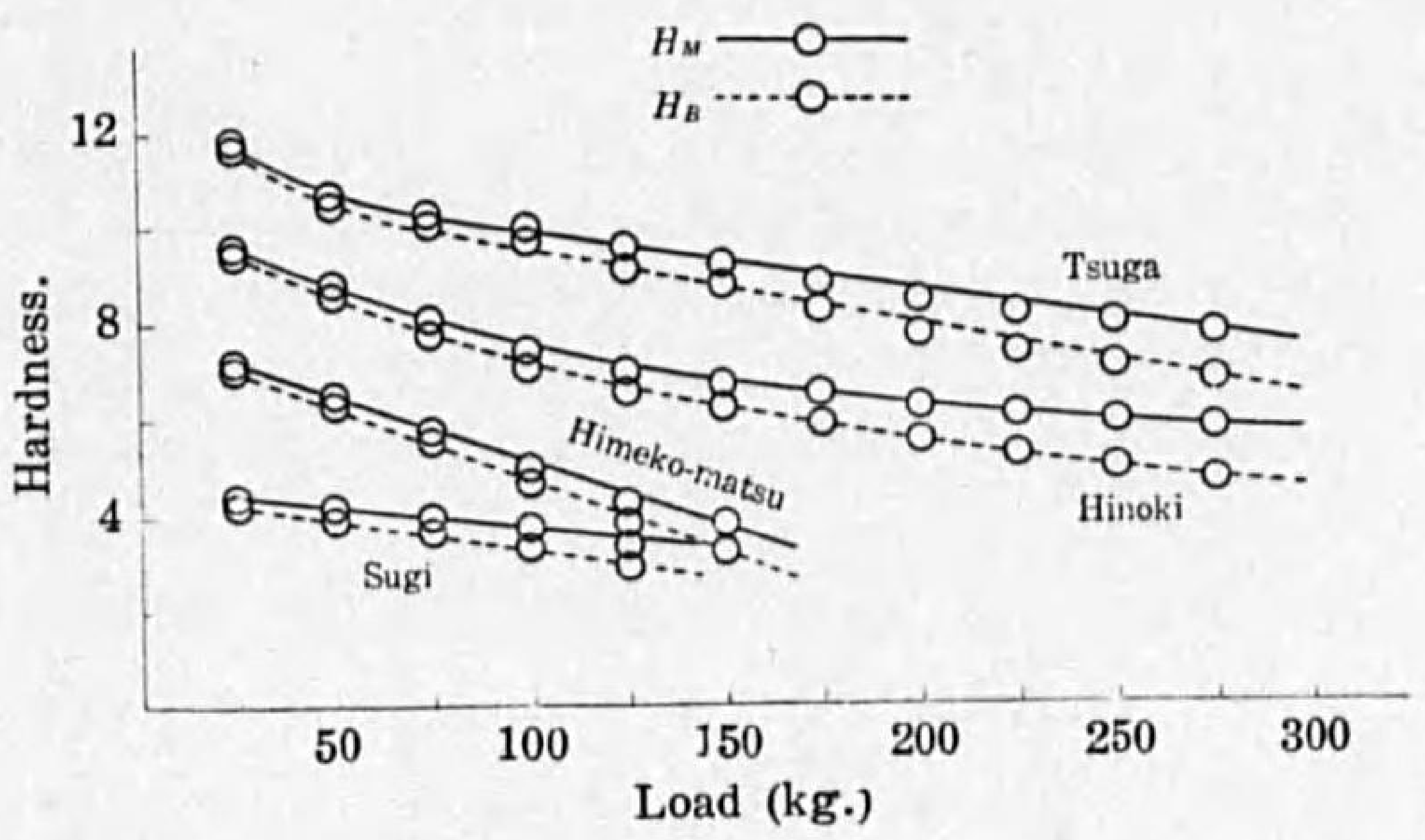
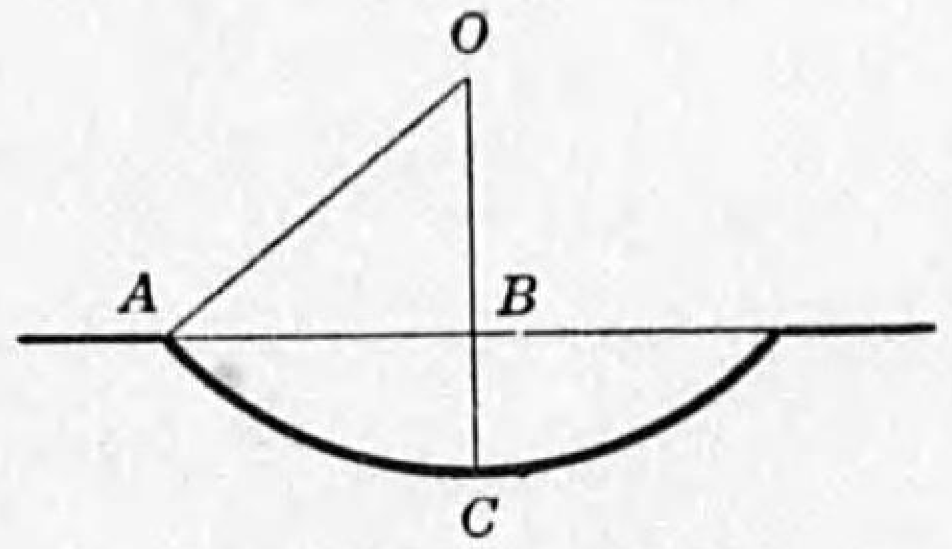


Fig. P.

Since $h$ and $D$ are positive and $h$ is not generally greater than $D/2$, $H_M$ is always greater than $H_B$. The less $h$ is, the more nearly $H_B$ come to $H_M$, and as $h$ increases, $H_B$ approaches nearer and nearer to one half of $H_M$.



$OA = OC = D/2$,
$AB = d/2$,
$BC = h$,
$AOB = \phi/2$.

Fig. Q.

## HARDNESS NUMBER OF WOOD EXPRESSED BY THE WORK DONE

In BRINELL's or MEYER's method, it is usual that the size of ball impression is not always equal, even if the fixed value is used for $P$, because the corresponding deformation of internal tissue of wood may vary with the properties of material, consequently the resistance of wood to the applied pressure may also vary. From this reason, it may be preferable that the hardness number of indentation is determined from the load which produces a fixed size of ball impression. In this case, however, when the load is increased above a certain point, it is very difficult to produce the given size of impression exactly on account of "creeping", so it may be convenient to carry on the test under comparatively small load.

In any case, since the relation of hardness to the applied load is represented by the curve as already shown, such hardness number just described indicates a certain point on the load-hardness curve and consequently it varies with the load to be applied. Therefore, it may be still better to express the hardness number by the work done to make the equal size of impression.

The hardness number just described above may be obtained as follows:

$$W = \int_0^{h_1} P\,dh\,,$$

where $W$ represents the work done.

But, $$P = ah^n\,,$$

$$\therefore \quad W = \int_0^{h_1} ah^n dh = \frac{a}{n+1}\,h_1^{n+1}.$$

If the volume of ball impression is represented by $V$,

$$V = \pi h_1^2\,(D/2 - h_1/3).$$

Then work per unit volume of the impression i.e. the energy indentation hardness ($H_e$) may be represented as follows:

$$H_e = W/V.$$

The energy hardness number may be represented by $W$ only, instead of being devided by the spherical volume $V$. It will, however, show its meaning more clearly that such quantity is represented by the work per unit volume.

It has already been described that in ball hardness test the less the indentation, the better. But when the load and the consequent impression is extremely small, owing to the influence of the friction of mechanical construction of depth isdicator, the friction of ram, the error due to mechanism of Bouldon tube etc., fair result may not be obtained. Furthermore, while an applied load lies comparatively small, an increase of the load causes a marked decrease in hardness number as shown in load-hardness curves. Therefore, even though it is quite right in theory to produce the extremely small impression in ball hardness test of wood, yet in practice, on the contrary, it may be liable to produce error. On the other hand, since the ball penetration shall not exceed the critical depth of indentation, value of limit $h_1$ shall not be taken beyond such a limit of depth.

In order to obtain the value of $H_e$ for each wood species, 0.5 mm. which is considered to be not excessive for any species tested was taken as the limit of integration. The values of $H_e$ for each species thus obtained are as follows:

TABLE VII.

| Species | He |
|---|---|
| *Shirakashi* | 13.08996 |
| *Nara* | 10.19444 |
| *Keyaki* | 9.84627 |
| *Kuri* | 9.51804 |
| *Katsura* | 6.55858 |
| *Harigiri* | 6.44104 |
| *Hohnoki* | 5.79995 |
| *Kihada* | 5.79647 |
| *Tsuga* | 9.75668 |
| *Hinoki* | 7.87417 |
| *Himeko-matsu* | 5.89263 |
| *Sugi* | 4.21123 |

## VARIATION OF HARDNESS NUMBER WITH DIAMETER OF BALL

Under a given load, hardness number of indentation when using balls of different sizes are not comparable, unless all results are reduced to a standard by means of a certain calculation. It is, therefore, more convenient to make all comparison tests with the same diameter of ball and weight of load. The values standardized by BRINELL are: $D = 10$ mm. and $P = 3{,}000$ kg. except for soft materials, when a value of $P = 500$ kg. may be used. It is certainly understood that BRINELL numbers based upon the different loads as just described, shall not be compared directly. Anyhow, these values are standardized for the testing of metals and it is widely recognized that they are not suitable for the testing of timber, consequently much lower load is generally applied in the latter test.

In accordance with the investigation made by C. BENEDICK (1904)(7), it was shown that, within the range of his test, the value of $P \times \sqrt[5]{D})/A$ was nearly constant, and that with a ball diameter $= D_1$ and load $(P)$ of 3,000 kg., BRINELL's hardness number $=$ $(P \times \sqrt[5]{D_1/10})/A$, where $A$ represents the spherical area of indentation (sq. mm.).

In order to allow for variation of pressure, H. Le CHATELIER(39) (1906) proposed the further modification:

$$H_B = \frac{P_1}{A_1} \times \sqrt[5]{\frac{D_1}{10}} \times \frac{20{,}000}{17{,}000 + P_1},$$

where $H_B =$ Brinell hardness number,
$P_1 =$ load employed (kg.),
$A_1 =$ spherical area of indentation calculated from the diameter (sq. mm.), and
$D_1 =$ diameter of the ball used.

Both the equations suggested by BENEDICK and Le CHATELIER are empyrical and only give approximate values.

E. MEYER(47) (1908) in his test of metals, showed the interesting result on the relation between the load and the diameter of ball as follows. According to his investigation, the mean pressure per unit

area $[4P/(\pi d^2)]$ is constant for a given angle of indentation whatever the diameter of the ball.

When an angle of spherical indentation is represented by$\varphi$ (see Fig. Q.)

$$d = D \sin(\phi/2)$$

and

$$H_M = 4P/\left\{\pi D^2 \sin^2(\phi/2)\right\},$$

where $P =$ pressure, $d =$ diameter
of impression and $D =$ diameter of ball.

It follows from MEYER's law of comparison that since $d/D$ and $4P/(\pi d^2)$ are constant for geometrically similar indentations on the same material, $P/D^2$ is also constant, in other words, for geometrically similar indentation, MEYER's hardness number is proportional to the load to be applied and inversely proportional to square of the diameter of ball. Just the same rule may be also applicable to the case of BRINELL hardness number $(H_B)$

$$H_B = \frac{P}{\frac{1}{2}\pi D \cdot (D - \sqrt{D^2 - d^2})} = \frac{P}{\pi D^2 \sin^2(\phi/4)}$$

$$\therefore \quad H_B \propto P/D^2 \text{ for a given } \phi.$$

This relation is useful where the wood piece to be tested is so small that a given pressure cannot be applied with a given size of ball. It is then only necessary to use a smaller ball and a load determined by the above relationship to obtain the standard hardness number required; thus if another size of ball whose diameter $= D_1$ is used, the corresponding load to be applied $(P_1)$ will be determined as follows:

$$P_1 = \frac{P \times D_1^2}{D^2}$$

In order to ascertain whether this relationship exists or not between the size of ball and the applied load in the hardness test of wood, the indentation tests were made with four different sizes of steel ball, i.e. 10 mm., 15 mm., 20 mm., and 25 mm. in diameter. The wood block were cut in size of $5 \times 5 \times 5$ cm.$^3$, and impressions were produced with respective ball on the same end surface which had been cleanly planed. The experimental data obtained are summarized in the Table VIII. Each value of $H_M$ and $\varphi/2$ in the Table VIII is the average of 30 impressions.

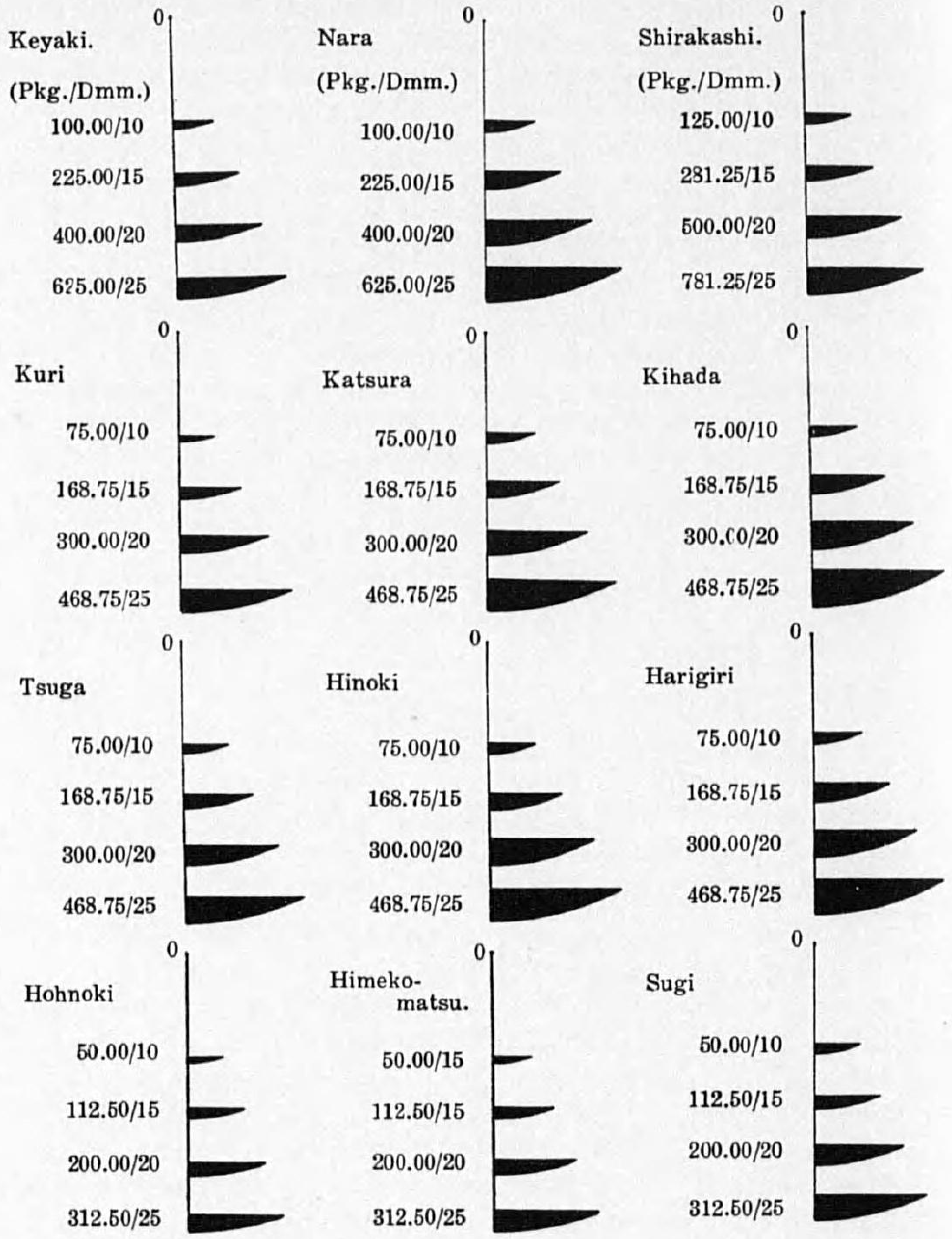


Fig. R.

The result shows comparatively good agreement of the hardness number obtained in this way. (see fig. R). And from the result above, it is observed that MEYER's hardness number, when using ball of larger diameter, is generally smaller than when using smaller ball. This reason may be explained by the different amount of flow of internal tissue of wood.

TABLE VIII.

| $D$ (mm.) | $P$ (kg.) | $H_M$ | $\phi/2$ |
|---|---|---|---|
| i. *Shirakashi.* | | | |
| 10 | 125.00 | 9.704 | 23° 54′ |
| 15 | 281.25 | 9.254 | 24° 31′ |
| 20 | 500.00 | 8.916 | 25° 02′ |
| 25 | 781.25 | 8.818 | 25° 09′ |
| ii. *Keyaki.* | | | |
| 10 | 100.00 | 9.160 | 21° 55′ |
| 15 | 225.00 | 9.234 | 21° 47′ |
| 20 | 400.00 | 8.933 | 22° 13′ |
| 25 | 625.00 | 8.491 | 22° 46′ |
| iii. *Nara.* | | | |
| 10 | 100.00 | 6.757 | 25° 44′ |
| 15 | 225.00 | 6.419 | 26° 25′ |
| 20 | 400.00 | 5.964 | 27° 27′ |
| 25 | 625.00 | 5.647 | 28° 22′ |
| iv. *Kuri.* | | | |
| 10 | 75.00 | 7.289 | 21° 14′ |
| 15 | 168.75 | 7.367 | 21° 07′ |
| 20 | 300.00 | 6.543 | 22° 28′ |
| 25 | 468.75 | 6.368 | 22° 46′ |
| v. *Katsura.* | | | |
| 10 | 75.00 | 5.491 | 24° 39′ |
| 15 | 168.75 | 5.214 | 25° 21′ |
| 20 | 300.00 | 4.943 | 26° 02′ |
| 25 | 468.75 | 4.740 | 26° 41′ |

TABLE VIII. (*Continued*)

vi. *Kihada.*

| $D$ (mm.) | $P$ (kg.) | $H_M$ | $\phi/2$ |
|---|---|---|---|
| 10 | 75.00 | 5.310 | 25° 06′ |
| 15 | 168.75 | 4.701 | 26° 49′ |
| 20 | 300.00 | 4.425 | 27° 42′ |
| 25 | 468.75 | 4.003 | 29° 13′ |
| vii. *Harigiri.* | | | |
| 10 | 75.00 | 4.999 | 25° 55′ |
| 15 | 168.75 | 4.962 | 26° 03′ |
| 20 | 300.00 | 4 473 | 27° 31′ |
| 25 | 468.75 | 4.207 | 28° 26′ |
| viii. *Tsuga.* | | | |
| 10 | 75.00 | 6.277 | 22° 59′ |
| 15 | 168.75 | 5.754 | 24° 01′ |
| 20 | 300.00 | 5.544 | 24° 31′ |
| 25 | 468.75 | 5.625 | 24° 20′ |
| ix. *Hinoki.* | | | |
| 10 | 75.00 | 5,047 | 25° 48′ |
| 15 | 168.75 | 4.946 | 26° 03′ |
| 20 | 300.00 | 4.492 | 27° 27′ |
| 25 | 468.75 | 4.450 | 27° 35′ |
| x. *Hohnoki.* | | | |
| 10 | 50.00 | 6.414 | 18° 22′ |
| 15 | 112.50 | 5.638 | 19° 38′ |
| 20 | 200.00 | 5.706 | 19° 31′ |
| 25 | 312.50 | 5.506 | 19° 52′ |
| xi. *Himeko-matsu.* | | | |
| 10 | 50.00 | 5.227 | 20° 26′ |
| 15 | 112.50 | 4.985 | 20° 55′ |
| 20 | 200.00 | 4.911 | 21° 06′ |
| 25 | 312.50 | 4.710 | 21° 36′ |

TABLE VIII. (*Continued*)

xii. *Sugi.*

| $D$ (mm.) | $P$ (kg.) | $H_M$ | $\phi/2$ |
|---|---|---|---|
| 10 | 50.00 | 4.039 | 23° 24′ |
| 15 | 112.50 | 3.952 | 23° 39′ |
| 20 | 200.00 | 3.968 | 23° 35′ |
| 25 | 312.50 | 3.678 | 24° 35′ |

## RELATION OF HARDNESS NUMBER TO MOISTURE CONTENT

It has been widely recognized that strength properties of wood change with changes in moisture content. The effect of moisture on the strength of wood has been very often investigated by BAUSCHINGER, JOHNSON, CLINE, TIEMANN, JANKA and many other writers and those results show that there is large increase in crushing strength, modulus of elasticity, stress at proportional limit and modulus of rupture with a decrease in the moisture content.

As might be expected, it was found in the present study that the similar relation exists between hardness number of indentation and the moisture content.

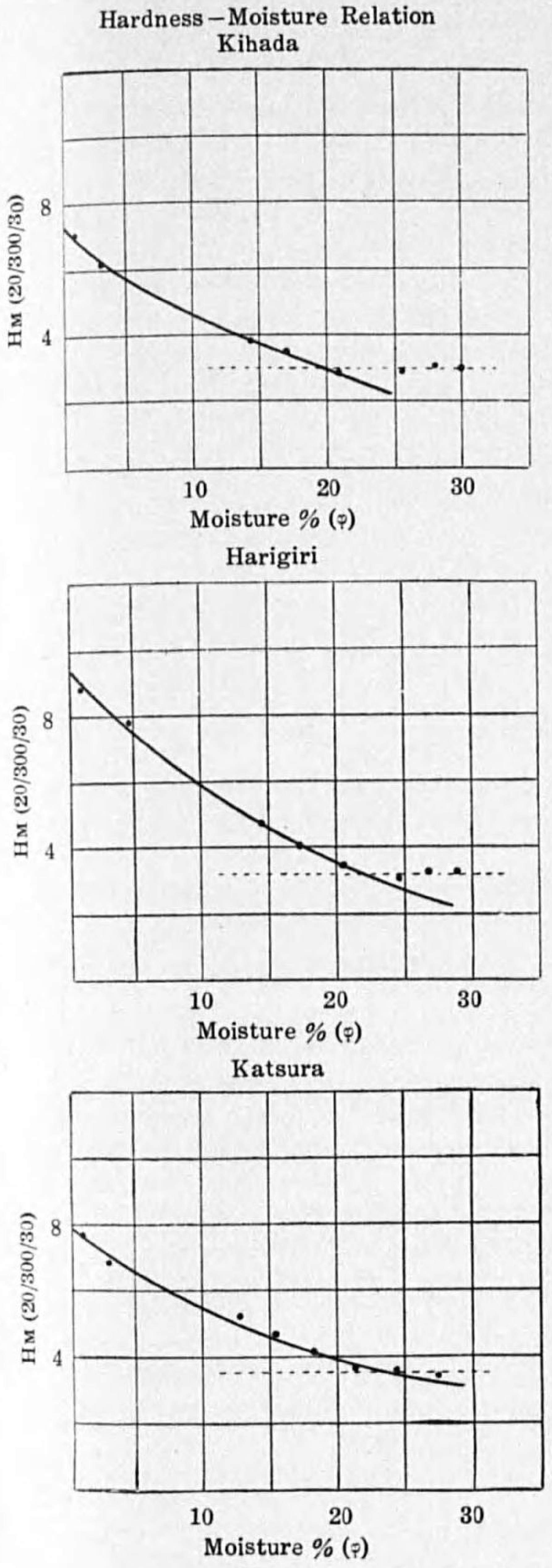
Since it is almost impossible to bring the wood blocks to be tested to the same moisture content before test, it is important for obtaining the comparable results that careful attention be given to the adjustment of hardness for differences of moisture content.

In order to find the relation of hardness to moisture content, experiment was carried out as follows.

The specimens to be tested were carefully cut in size 3 × 3 × 2 cm.$^3$ and the surfaces were clearly planed. These blocks were divided into several groups and some groups dried in oven and the other were kept in moist air at different length of time in order to bring each to a different moisture degree. After drying or moistening in this way, 20 mm. ball was pressed into the end surface of each specimen under a load of 300 kg., and the effect of varying degrees of moisture on hardness number was observed. For a species, wood blocks to be tested should be of course confined within reasonable range of specific gravity. From the experimental data which are shown in Table IX, the moisture-hardness relation was derived as shown in fig. S.

TABLE IX.

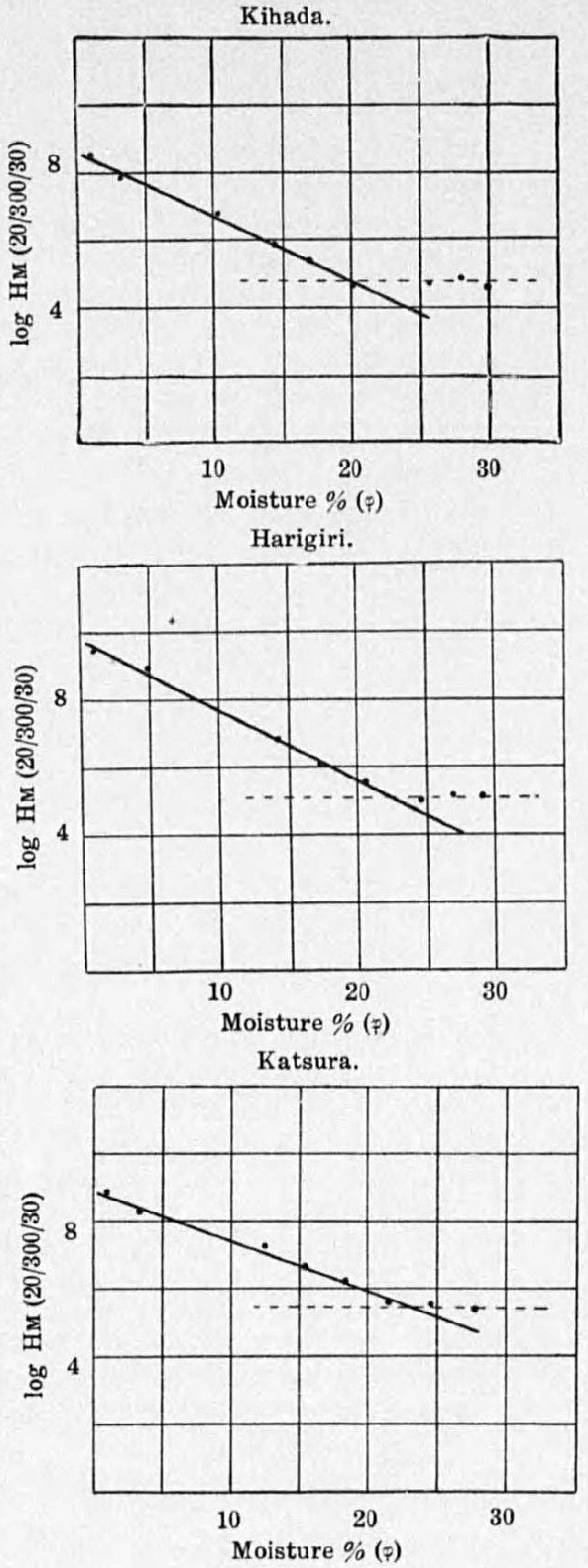
| Species | number tested | Sp. gr. | $H_2O$ % | $H_M$ |
|---|---|---|---|---|
| a. *Kihada.* | 30 | .358 | 0.817 | 7.087 |
| | 30 | .333 | 3.164 | 6.162 |
| | 30 | .382 | 14.483 | 3.868 |
| | 30 | .387 | 16.962 | 3.508 |
| | 30 | .371 | 20.944 | 2.904 |
| | 12 | .408 | 25.572 | 2.921 |
| | 15 | .423 | 28.016 | 3.089 |
| | 10 | .425 | 30.118 | 3.014 |
| b. *Harigiri.* | 30 | .452 | 0.963 | 8.853 |
| | 30 | .494 | 4.707 | 7.898 |
| | 30 | .501 | 14.214 | 4.799 |
| | 30 | .487 | 17.432 | 4.065 |
| | 30 | .497 | 20.455 | 3.505 |
| | 12 | .479 | 24.638 | 3.174 |
| | 13 | .409 | 26.803 | 3.290 |
| | 13 | .451 | 29.031 | 3.277 |
| c. *Katsura.* | 30 | .414 | 0.868 | 7.773 |
| | 30 | .382 | 3.159 | 6.833 |
| | 30 | .434 | 12.958 | 5.367 |
| | 30 | .451 | 15.442 | 4.654 |
| | 30 | .442 | 18.299 | 4.165 |
| | 12 | .430 | 21.448 | 3.638 |
| | 12 | .410 | 24.492 | 3.567 |
| | 12 | .436 | 27.528 | 3.498 |


Hardness—Moisture Relation
Kihada

Harigiri

Katsura

Fig. S.


Kihada.

Harigiri.

Katsura.

Fig. T.

From the diagrams it will be seen that with increase of moisture content the hardness number at first falls off more or less rapidly and then slowly until a certain moisture per cent is reached. That the reduction of the amount of moisture of wood is accompanied by an increase of hardness number, might result from a progressive decrease in cohesion of the micellae owing to the reduced friction between them. Above that per cent a further increase in moisture content has almost no effect on the hardness number and consequently the moisture-hardness curve becomes almost horizontal line. This relation just described is almost similar to the strength-moisture relation. A point on the curve where the hardness abruptly ceases to decrease is known as fiber satulation point. Within the range of the present study, it was estimated that the moisture per cent at the fiber satulation point confine to 20–24% approximately.

BAUSCHINGER determined the relation between the crushing strength and the moisture content and found that:

$$\beta_0 = \beta \left\{1+\lambda\,(\varphi-\varphi_0)\right\},$$

where $\beta$ is crushing strength in $\varphi$ per cent moisture content, $\beta_0$ is that in lower moisture content $\varphi_0\%$ in air dry condition, and $\lambda$ is constant for wood species.

In very narrow range of moisture content, such a linear equation as above may be also applicable in moisture-hardness relation, yet in general, the relation may not be represented by such a simple linear equation.

It was found that when logarithm of hardness number is plotted against the moisture per cent the points could be averaged by a straight line as shown in fig. T, and the equations of these lines were obtained by means of calculation (least square) as follows:

| | |
|---|---|
| *Kihada* | $\log H_M = -0.0191207\,\varphi+0.86267,$ |
| *Harigiri* | $\log H_M = -0.0212278\,\varphi+0.98116,$ |
| *Katsura* | $\log H_M = -0.0145208\,\varphi+0.89581,$ |

where $\varphi$ is moisture per cent below the fiber satulation point. The relation between hardness and moisture per cent, therefore, will be represented by the exponential equation:

$$H_M = H_0\, e^{-k\varphi},$$

where $H_0$ = hardness at absolutely dry state and $k$ = constant for the species.

Values of $H_0$ and $k$ calculated for the species tested are as follows:

| | | |
|---|---|---|
| *Kihada* | $H_0 = 7.2891$ | $k = 0.044026$ |
| *Harigiri* | $H_0 = 9.5755$ | $k = 0.048878$ |
| *Katsura* | $H_0 = 7.8671$ | $k = 0.033435$ |

Since the relation of $\log H$ to $\varphi$ can be represented by a straight line as described above, the same relation may also be represented by the following equation:

$$\frac{\varphi_s-\varphi_1}{\varphi_s-\varphi_2} = \frac{\log H_1-\log H_s}{\log H_2-\log H_s},$$

where $\varphi_s$ = moisture per cent at fiber satulation point,
$\varphi_1$ = moisture per cent of dried material at time of test,
$\varphi_2$ = moisture per cent to which it is desired to adjust,
$H_s$ = hardness number at fiber satulation point,
$H_1$ = hardness number at $\varphi_1$,
$H_2$ = hardness number at $\varphi_2$,

then, $$\log \frac{H_2}{H_s} = \frac{\varphi_s-\varphi_2}{\varphi_s-\varphi_1}\log \frac{H_1}{H_s}.$$

If $H_s$ and $\varphi_s$ are known, hardness number $H_1$ at the time of test will be reduced to a hardness number at moisture content desired to adjust. Ratio $H_1/H_s$ or $H_2/H_s$ in the above equation is just similar to the improvement ratio defined by WILSON(78) in the strength-moisture relation.

## SPEED OF LOADING

Speed of loading often plays an important part in the behavior of materials under stress. Variation in the rate of applying load in the static ball indentation test of wood, may have also an effect to a certain degree on the hardness number and the manner of deformation though it may be not so distinct.

In order to find the effect of variations in the rate of applying load in the ball indentation test, 20 mm. diameter ball was pressed into the end surface of wood blocks including 6 species under different speed of loading.

Each specimen was carefully cut in size 3 × 3 × 2 cm.$^3$ and the surfaces were clearly planed, and tested in air dry condition i.e. the moisture content was confined within the range from 13 to 17 per cent of dry weight.

Specimens of each wood species to be tested were divided in three groups according to the speed of loading* to be applied i.e. quick (60 kg. per second), medium (20 kg. per second), and slow (10 kg. per second). Hardness number [$H_{M(20.300/30)}$] obtained under each rate of loading are shown in Table X.

TABLE X.

| Species | number tested | Sp. gr. | $H_2O$ % | Rate of Loading (kg./sec.) | $H_M$ |
|---|---|---|---|---|---|
| *Shirakashi* | 30 | .833 | 14.03 | 60 | 7.932 |
| | 30 | .839 | 13.46 | 20 | 7.795 |
| | 30 | .837 | 13.20 | 10 | 7.754 |
| *Keyaki.* | 30 | .608 | 14.22 | 60 | 6.041 |
| | 30 | .620 | 14.36 | 20 | 5.991 |
| | 30 | .614 | 14.41 | 10 | 5.982 |
| *Harigiri* | 30 | .448 | 14.53 | 60 | 3.952 |
| | 30 | .441 | 14.11 | 20 | 3.883 |
| | 30 | .448 | 13.83 | 10 | 3.900 |
| *Kihada* | 30 | .412 | 14.71 | 60 | 3.824 |
| | 30 | .412 | 14.42 | 20 | 3.807 |
| | 30 | .414 | 14.45 | 10 | 3.725 |
| *Kuri* | 30 | .455 | 16.50 | 60 | 3.729 |
| | 30 | .452 | 16.18 | 20 | 3.565 |
| | 30 | .455 | 15.77 | 10 | 3.629 |
| *Katsura* | 30 | .349 | 13.78 | 60 | 3.527 |
| | 30 | .352 | 13.71 | 20 | 3.491 |
| | 30 | .351 | 13.65 | 10 | 3.485 |

---

* Each speed of loading was measured with two stop watches at a time.

According to the result in the Table X, no consistent effect is recognized in hardness number under the medium and the slow loading, while under the quick loading, hardness number appears to show a tendency to be slightly increased. (see fig. U). But, quick loading as described above is not used in ordinary static indentation test because this rate of loading is too rapid for the convenient performance of the test, and the load is usually applied more gradually. Therefore, it may be said that ordinary variations in the rate of loading have practically no consistent effect on the static ball indentation hardness of wood.

Influence of the speed of loading upon hardness.

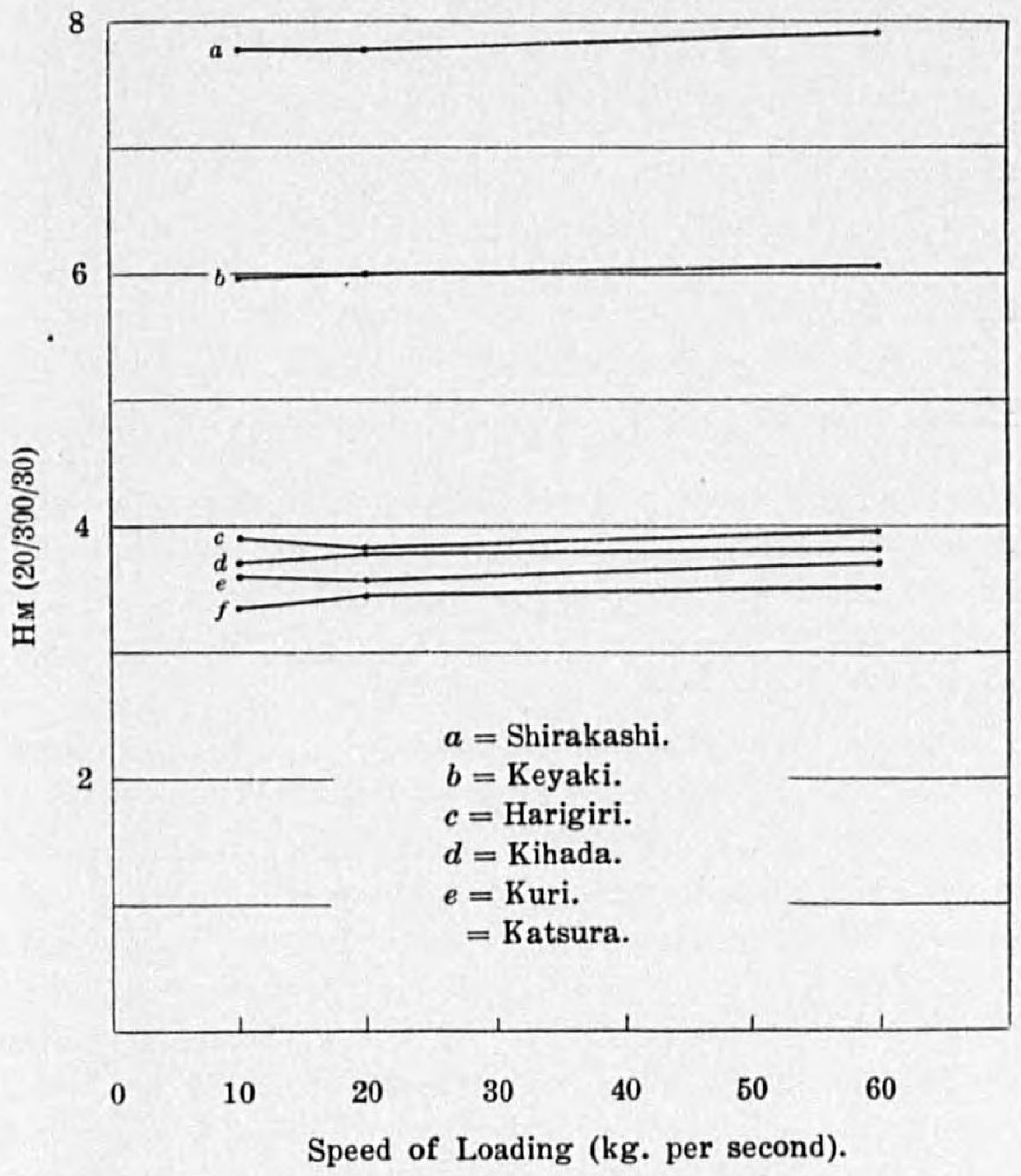


Fig. U.

It was recognized that under the same applied load, as a rule, the specimen is more easily broken by quick loading than by gradual loading, in other words, the critical depth of indentation is decreased by increasing the speed of loading.

According to the investigation of metals made by P. LUDWICK(42), there are two types of failure, one is named "sliding failure" and the other" "separation failure". This theory of failure may be applicable in some extent in the case of fiber wall of wood which consists of infinitesimal crystalline units. In the case of brittle materials, fracture occurs without appreciable deformation. This is a separation failure. In some materials, considerable deformation takes place before fracture occurs. This is a sliding failure. In studying these types of failure, the theory has been forwarded that the strength of a material can be described by two characteristics, the resistance of the material to separation and the resistance to sliding. If the resistance to sliding is greater than the resistance to separation, fracture will occur as a result of overcoming cohesive forces without appreciable deformation. If the resistance to separation is larger than resistance to sliding, the sliding over inclined planes begins first and fracture occurs only after a considerable deformation.

The relation between the resistance to separation and the resistance to sliding does not remain constant for the same material. It depends very much upon the velocity of deformation.

There are evidences that the resistance to sliding increases as the velocity of deformation increases. This would explain, within a certain extent, why a wood piece is deformed without cracking under slow loading while the same piece is fractured without appreciable deformation under quick loading. A good example of this is bird-lime. It may easily flow under the action of its own weight, but under the quick applied forces it will be pull apart more or less like brittle material. This shows that the resistance to sliding was less than the resistance to separation under slow deformation and vice versa under high speed deformation.

Therefore it may be concluded that the resistance to sliding is increased and the resistance to separation is decreased by increasing the rate of loading.

## LIST OF SPECIES USED

| | |
|---|---|
| *Aka-ezomatsu* | *Picea Glehnii* MAST. |
| *Aka-matsu* | *Pinus densiflora* SIEB. ET ZUCC. |
| *Harigiri* | *Kal panax ricinifolium* MIQ. *var. typicum* NAKAI. |
| *Himeko-matsu* | *Pinus parviflora* SIEB. ET ZUCC. |
| *Hinoki* | *Chamaecyparis obtusa* SIEB. ET ZUCC. |
| *Hohnoki* | *Magnolia obovata* THUNB. |
| *Karamatsu* | *Larix Kaempferi* SARG. |
| *Katsura* | *Cercidiphyllum japonicum* SIEB. ET ZUCC. |
| *Keyaki* | *Zerkowa serrata* MAKINO. |
| *Kihada* | *Phellodendron amurense* LUPR. |
| *Kiri* | *Paulownia tomentosa* STEUD. |
| *Kunugi* | *Quercus acutissima* CARR. |
| *Kuri* | *Castanea crenata* SIEB. ET ZUCC. |
| *Maguwa* | *Morus alba* L. |
| *Momi* | *Abies firma* SIEB. ET ZUCC. |
| *Nara* | *Quercus serrata* THUNB. |
| *Shii* | *Shiia Sieboldi* MAKINO. |
| *Shirakashi* | *Quercus myrsinaefolia* BLUME. |
| *Shonan-boku* | *Libocedrus macrolepis* BENTH. |
| *Sugi* | *Cryptomeria japonica* D. DON. |
| *Togasawara* | *Pseudtsuga japonica* BEISSN. |
| *Tsuga* | *Tsuga Sieboldii* CARR. |
| *Tsuge* | *Buxus japonica* MUEL. ARG. |

* * *

## SUMMARY AND CONCLUSIONS

1. In the ball indentation test of wood, it is dangerous to apply an arbitrary load, and the load should always be applied within a certain limit.

2. It is important that the hardness number of indentation should be obtained by the applied load and the corresponding deformation without any fracture.

3. After the wood block is broken by excessive penetration of ball, it will not indicate the essential resistance, hence, JANKA's method of testing can not be said reasonable.

4. When the fracture takes place due to excessive penetration, the area of the injured part will have a widely different aspect. In this case, the deformed region is divided into two separated parts.

5. In the case of obtaining the hardness number of wood from diameter of ball impression, mean diameter is preferable to be taken as the basis of spherical area computation.

6. The manner of fracture at initial stage due to ball indentation appears to be closely related with the anatomical feature of wood species.

7. Regional spread of deformation of wood element is comparatively regular and the injured part is distinguishable from uninjured region surrounding it on account of the difference of luster.

8. By careful observation, along the border of the injured area, the lines of yielding are observed as more or less curved lines jut out from injured area into uninjured region surrounding it. This pattern appears to a certain degree to follow the mechanical theory of plastic deformation.

9. The reason why no slip line crosses through the middle lamella may be partly explained by its isotropic or amorphous condition.

10. Owing to the marked difference of micellular arrangement, the pit in the wall is considered to be closely related with the commencement of failure.

11. Within a certain limit, the relation of the depth of indentation ($h$) to the applied load ($P$) is represented by the equation:

$$P = ah^n ,$$

where the value of $n$ is less than unity.

12. The time during which the pressure is applied is most marked up to about 30 seconds' application of load and after that the effect is very small.

13. In choosing the place on the block for the indentation, it is important to get a fair average of early and late wood zones. For this purpose, it may be convenient to use 20 mm. diameter ball instead of smaller ball which has been usually used in indentation hardness test of wood.

14. Although it is right in theory to produce the extremely small impression, yet in practice, it may be liable to produce error.

15. The rightness of MEYER's law of comparison has been ascertained by the present research in regard to the indentation test of wood.

16. Ordinary variations in the rate of loading have practically no consistent effect on the static ball indentation test of wood, although, under extremely quick loading, hardness number appears to show a tendency to be slightly increased.

17. In the static indentation test of wood, the present writer brings forward that $H_{(20\ 300/30)}$ is taken as a standard.

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## DESCRIPTION OF PLATES

### PLATE I.

Fig. 1. Line of fracture due to excessive penetration. (*Harigiri*) ×7/10.

Fig. 2. do. (*Katsura*) ×7/10.

Fig. 3. Regional spread of deformation within critical depth of indentation. (*Hinoki*) By SUMP pressing method. ×5.

Fig. 4. Regional spread of deformation due to excessive penetration. (*Hinoki*) SUMP pressing method. ×5.

Fig. 5. Regional spread of deformation within critical depth of indentation. (*Shirakashi*) SUMP. ×5.

Fig. 6. do. (*Sugi*).

Fig. 7. do. (*Karamatsu*).

Fig. 8. do. (*Katsura*).

### PLATE II.

Fig. 9. Regional spread of deformation within critical depth of indentation. (*Kiri*) SUMP. ×5.

Fig. 10. do. (*Hohnoki*).

Fig. 11. A part of deformed area observed under microscope with "Ultropak" objective. (*Hinoki*) ×15.

Fig. 12. do. (*Kiri*).

Fig. 13. Lüders' lines in an end compression specimen. (*Maguwa*) ×8/10.

Fig. 14. do. (*Harigiri*).

### PLATE III.

Fig. 15. Lüders' lines in an end compression specimen observed under microscope with "Ultropak" objective. (*Kihada*). ×33.

Fig. 16. do. (*Maguwa*).

Fig. 17. Line of flow jut out from injured area to unaltered area surrounding it. (*Hinoki*) [Ultropak objective.] ×33.

Fig. 18. do. (*Hohnoki*).

Fig. 19. Line of flow due to ball penetration in the vicinity of injured area. (*Harigiri*) [Ultropak objective.] ×33.

Fig. 20. Laminar type of deformation photographed with polarized light. (*Kiri*) ×65.

### PLATE IV.

Fig. 21. Strain figure of plastic deformation produced by pressure of cylinder on flat surface of clay.

Fig. 22. Crackings of brittle coating at region of stress concentration. ×4.

Fig. 23. Line of flow produced in the summer wood by ball penetration. Section was stained with Aniline chloride followed by Aniline blue. (*Tsuga*) ×200.

Fig. 24. do. Stained with Safranin followed by Aniline blue. (*Tsuga*) ×200.

### PLATE V.

Fig. 25. Stress distribution in a plate of celluloid subjected to penetration. The bands of equal darkness or brightness are lines of constant color that is so-called Isochromatic lines.

Fig. 26. Isoclinic lines (at 0°).

Fig. 27. Slip lines in the wall of summerwood tracheid photographed with polarized light. (*Karamatsu*) ×625.

Fig. 28. do. (*Sugi*). ×625.

### PLATE VI.

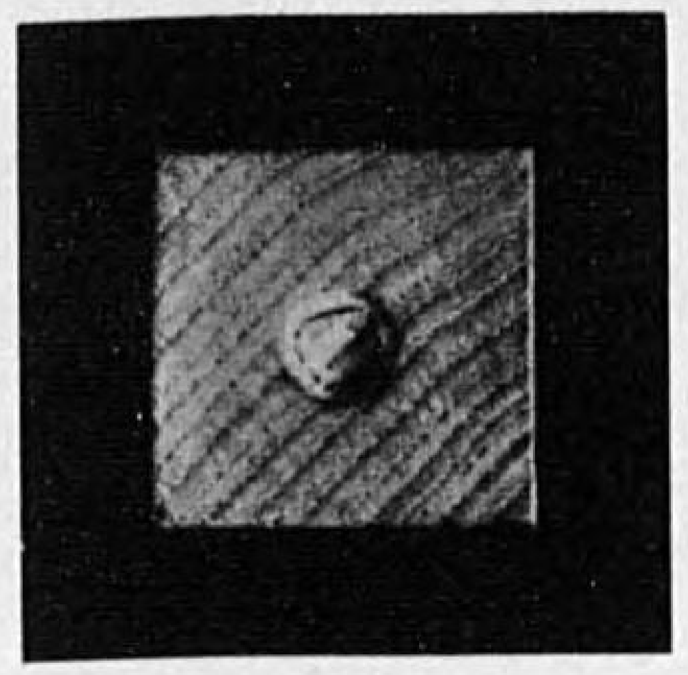
Fig. 29. Slip lines in the wall of wood fiber of *Kunugi* photographed with polarized light. ×200.

Fig. 30. Slip lines in the wall of spring tracheid of *Himekomatsu* not subjected to any mechanical test. ×500.

Fig. 31. Pits of spring tracheid of *Momi* observed under crossed Nicols. Axis of fiber is in a position of parallel or perpendicular to the axis of either Nicols. ×230.

Fig. 32. do. rotating the stage of microscope 45° from above position. ×230.

PLATE I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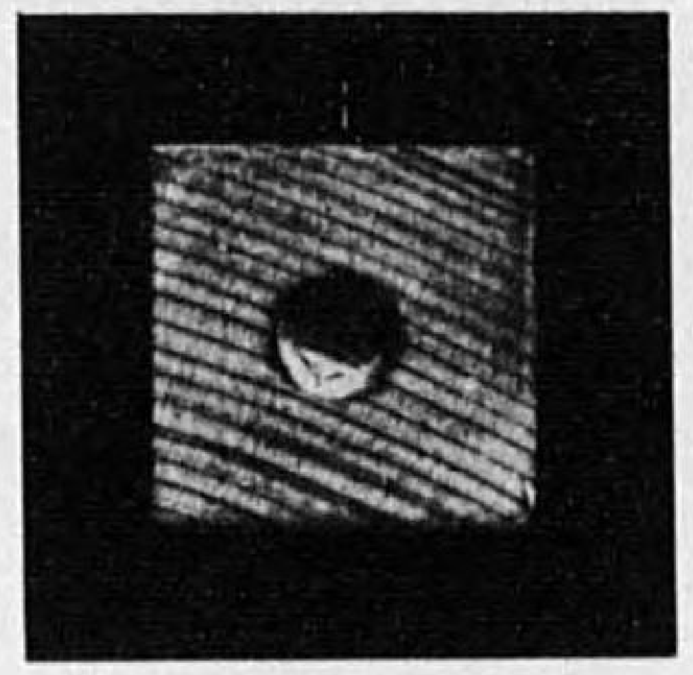
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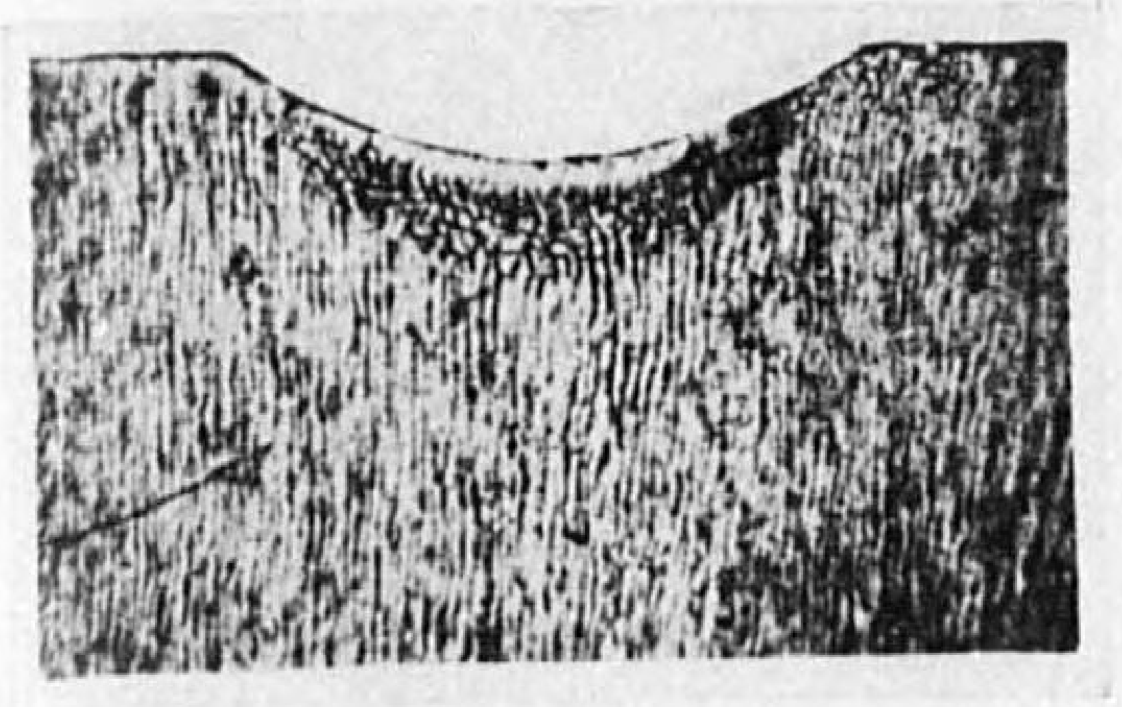
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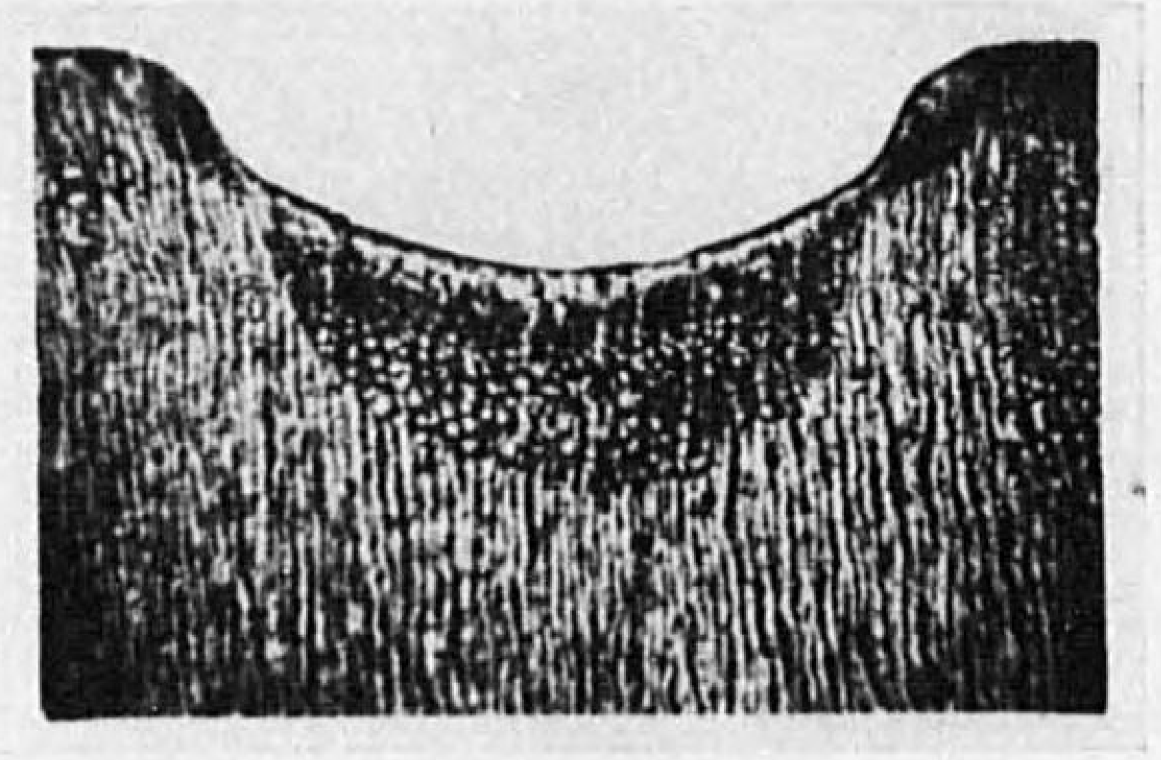
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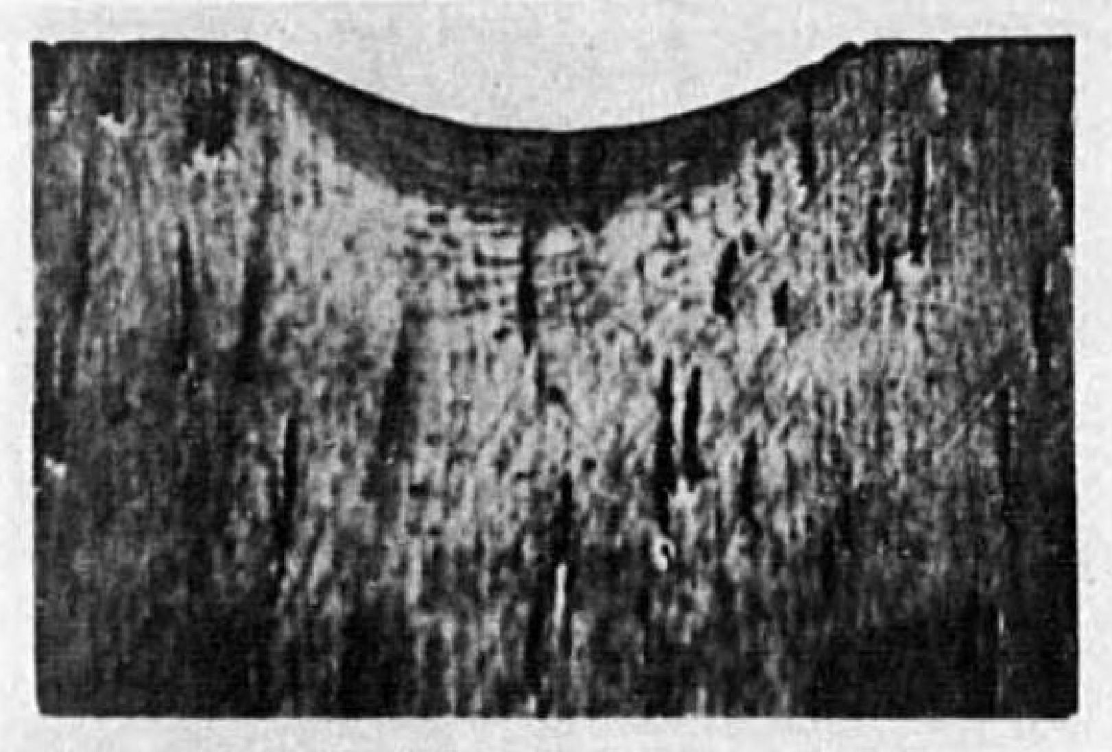
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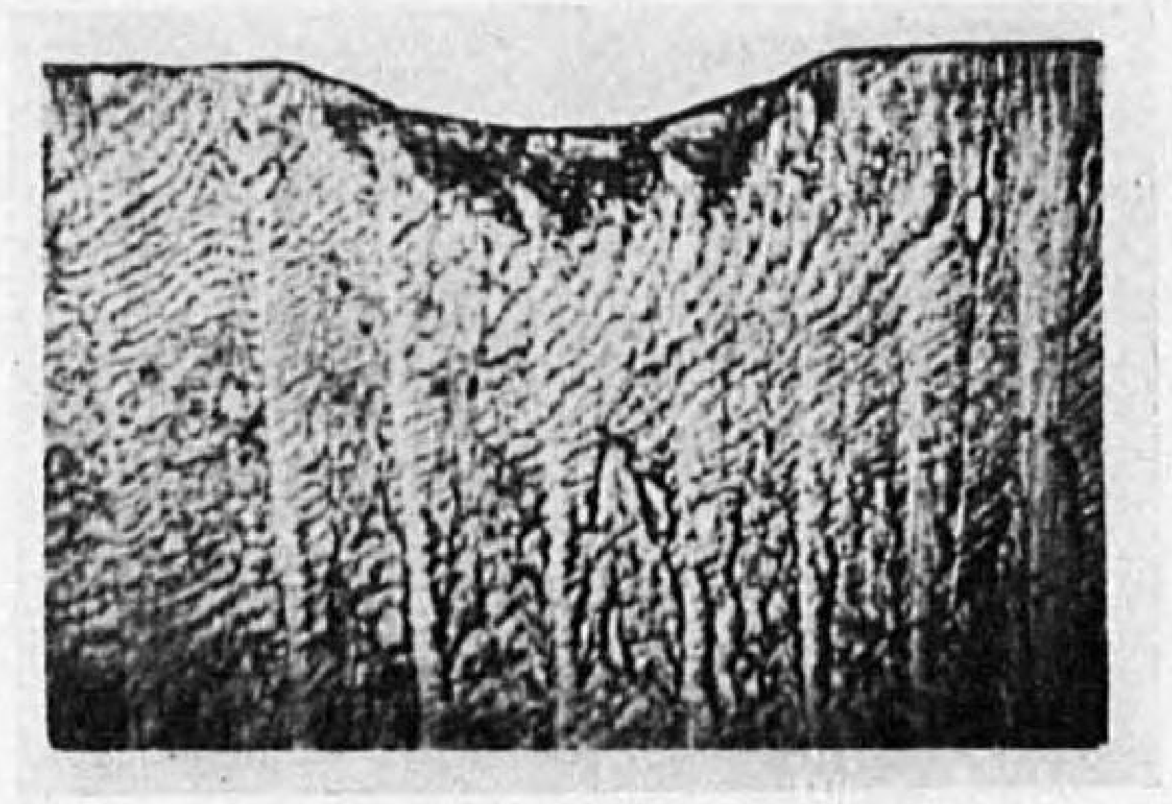
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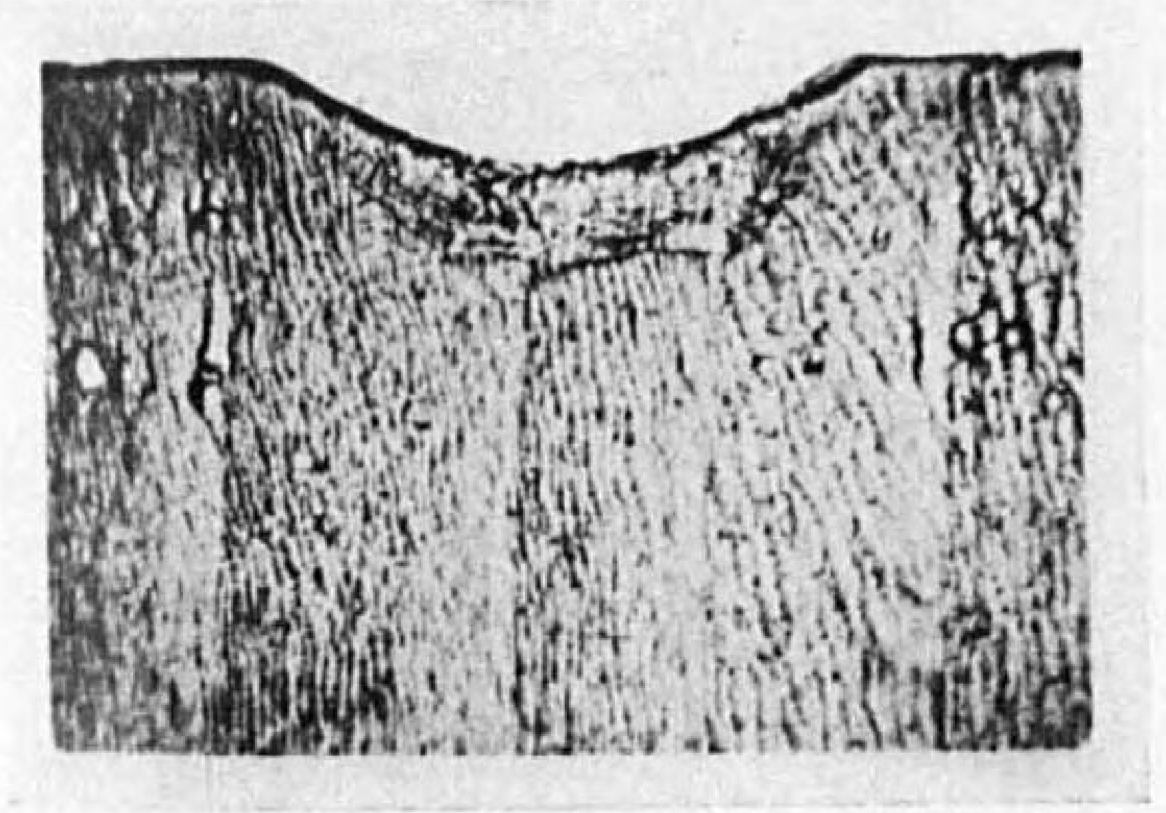


Fig. 7

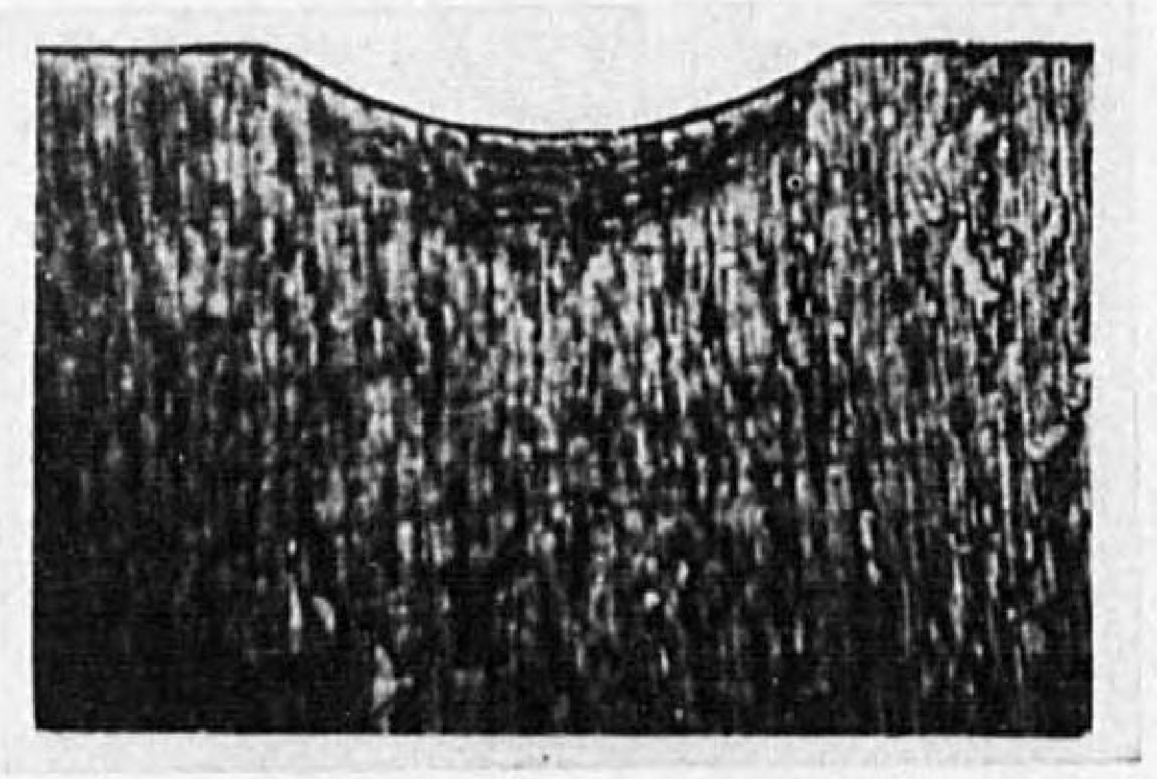


Fig. 8

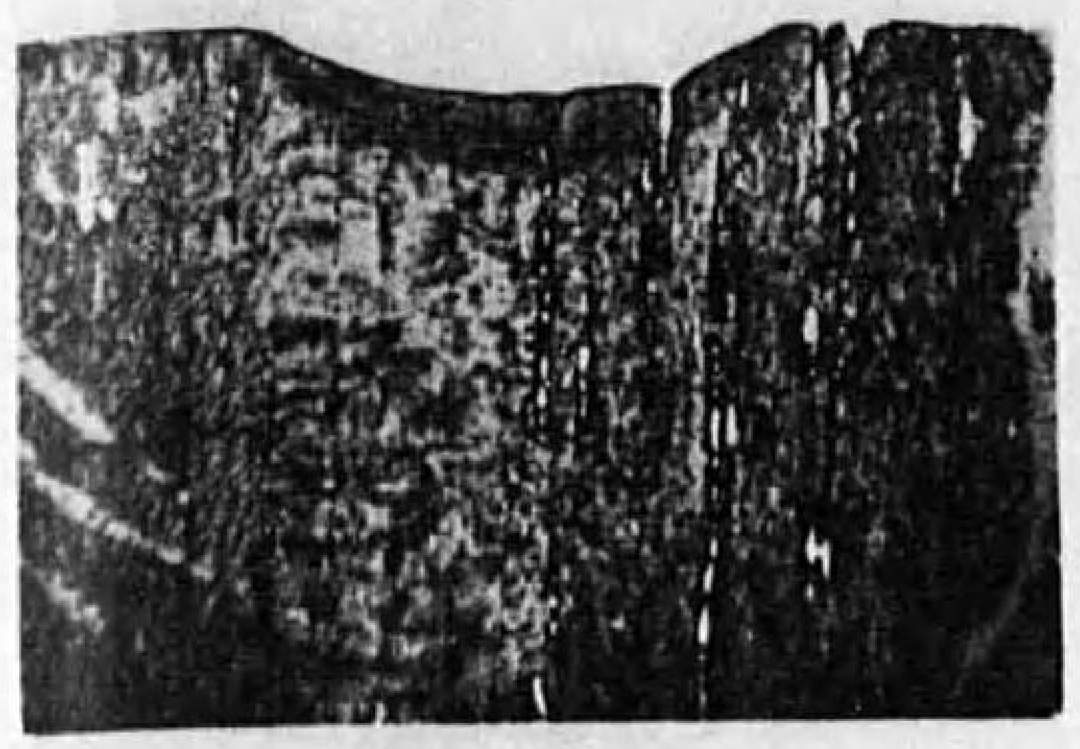


Fig. 9

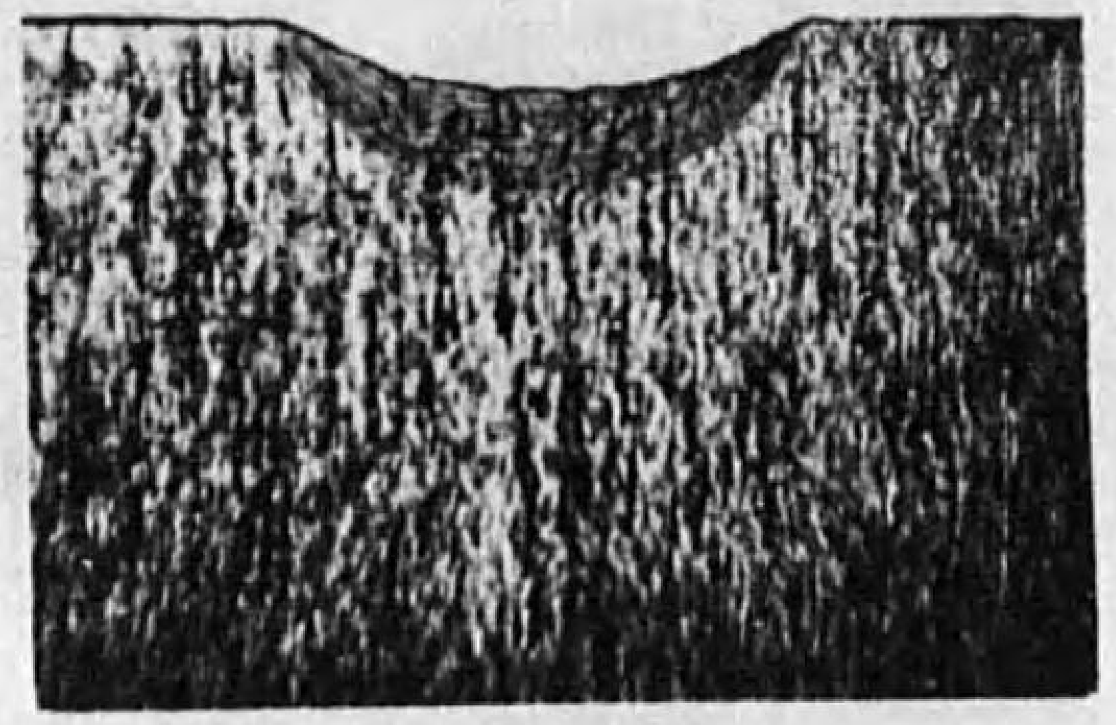


Fig. 10

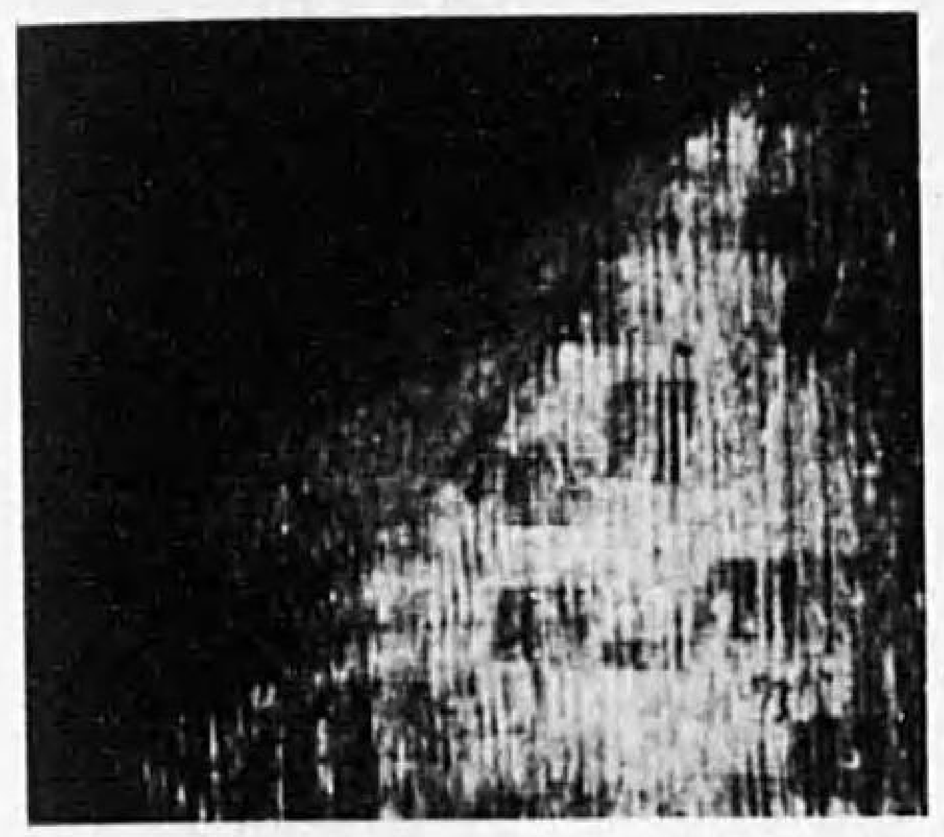
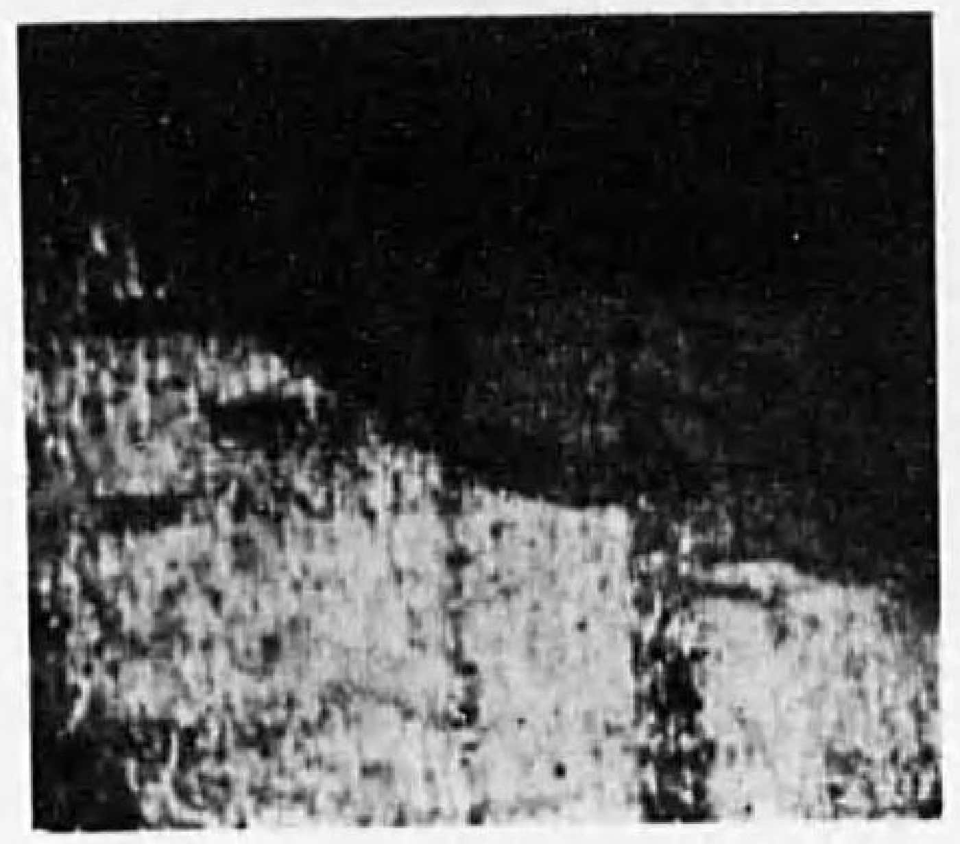


Fig. 11



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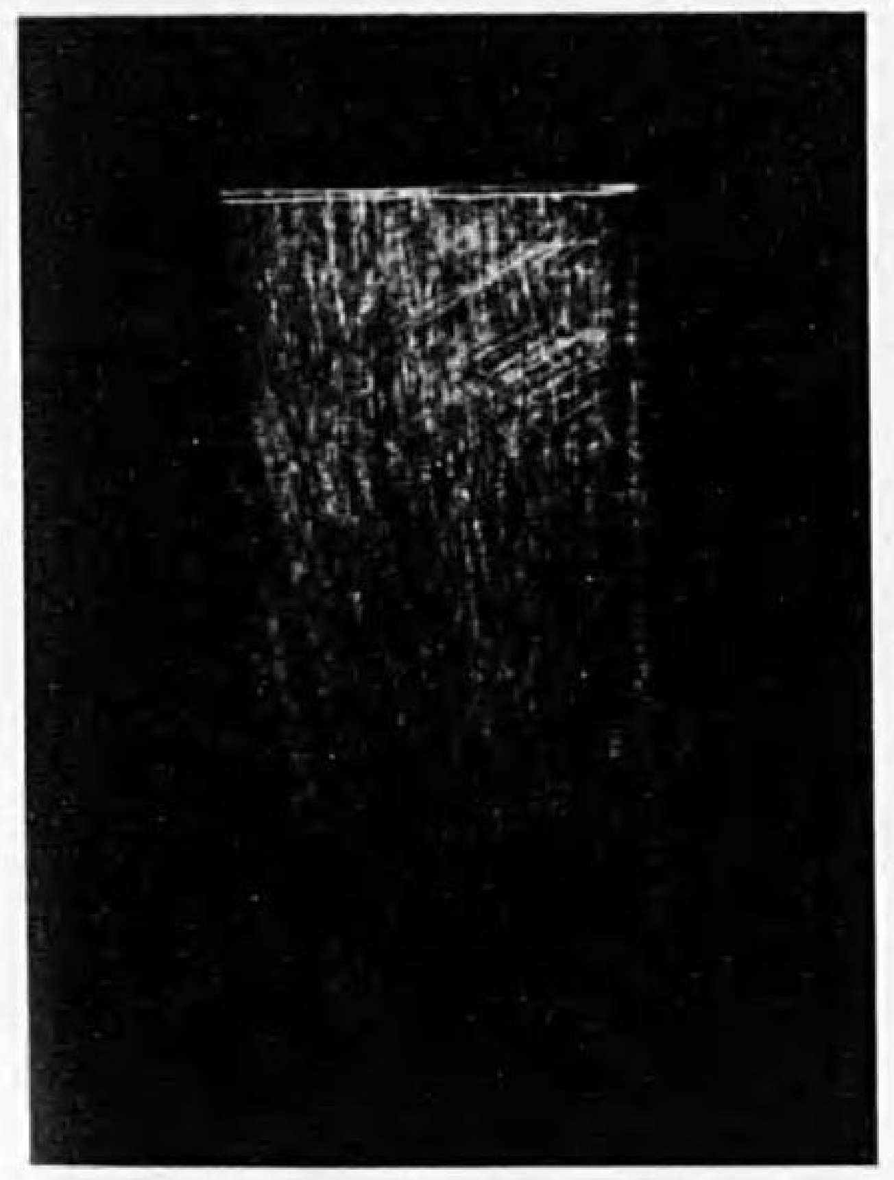


Fig. 13

Fig. 14

Fig. 15

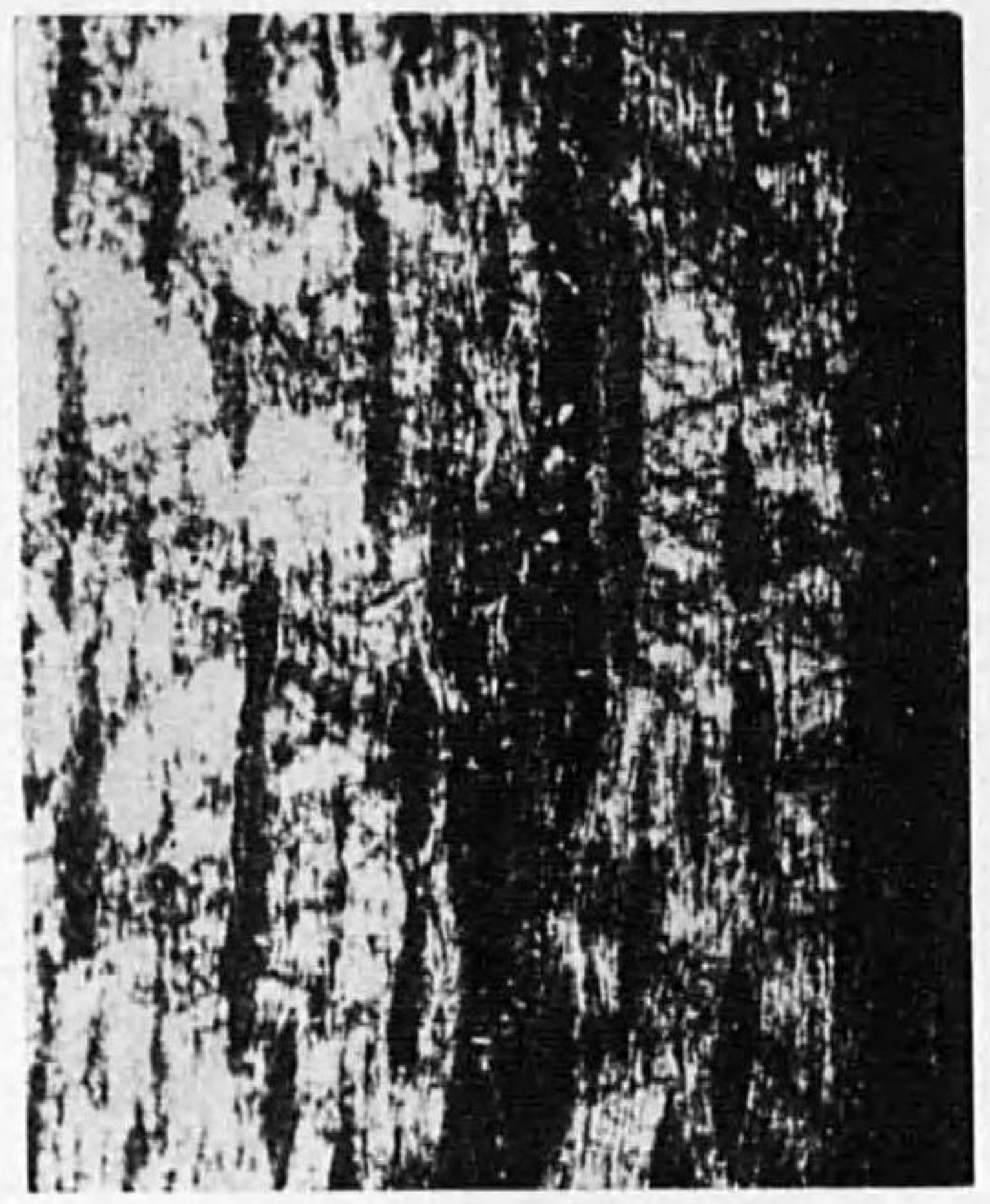


Fig. 16

Fig. 17

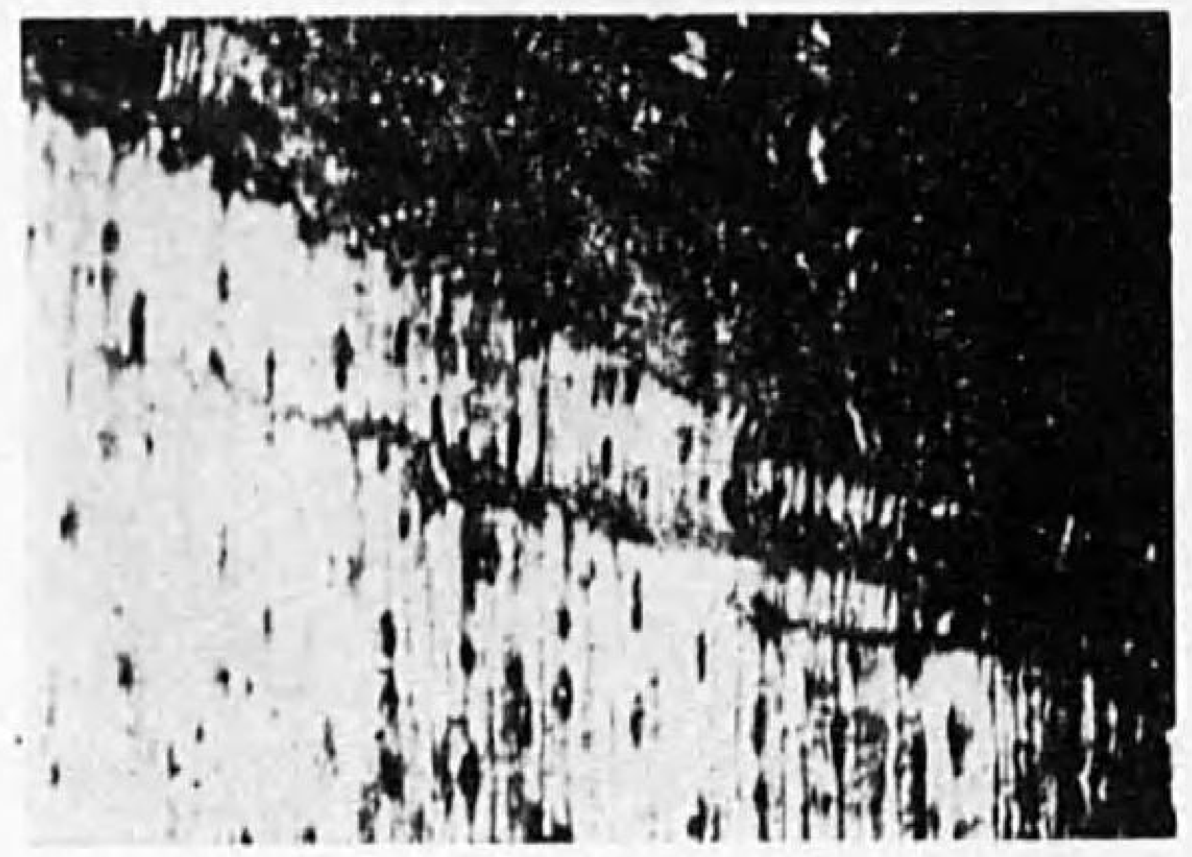
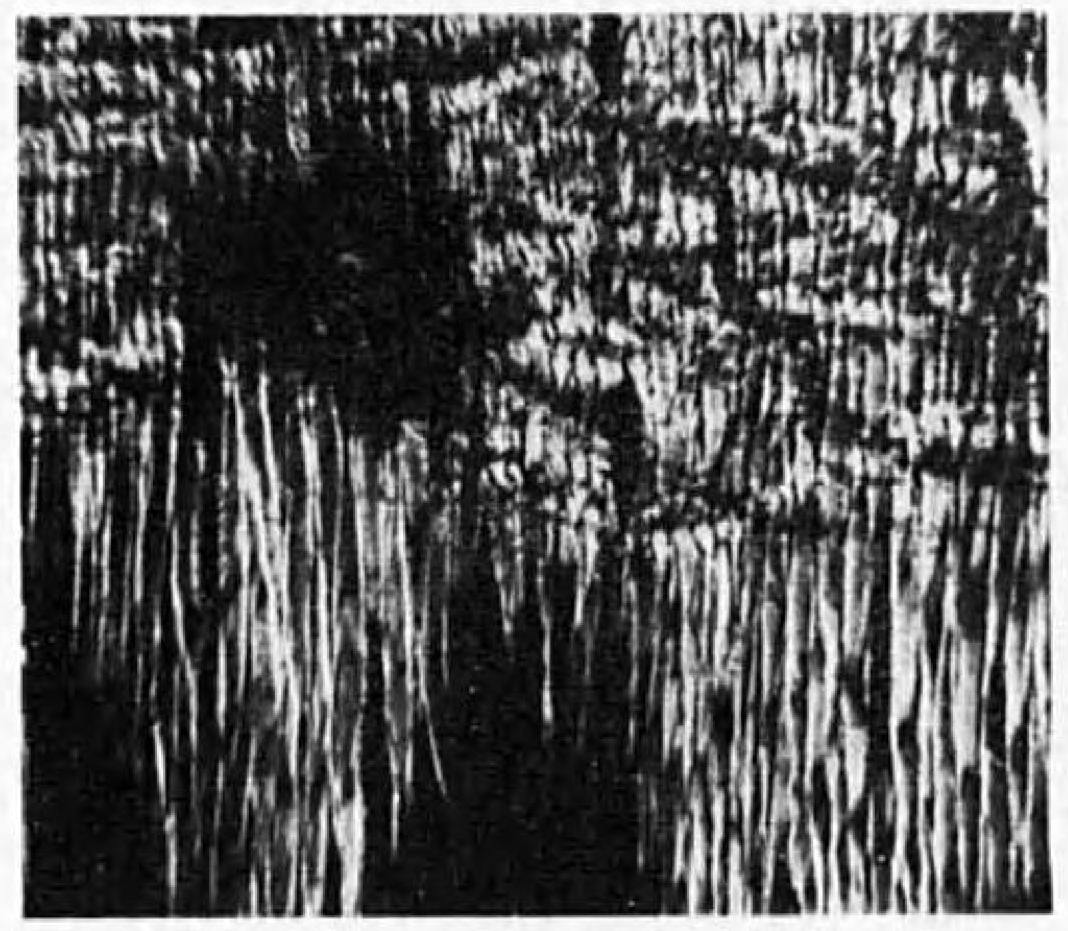


Fig. 18

Fig. 19



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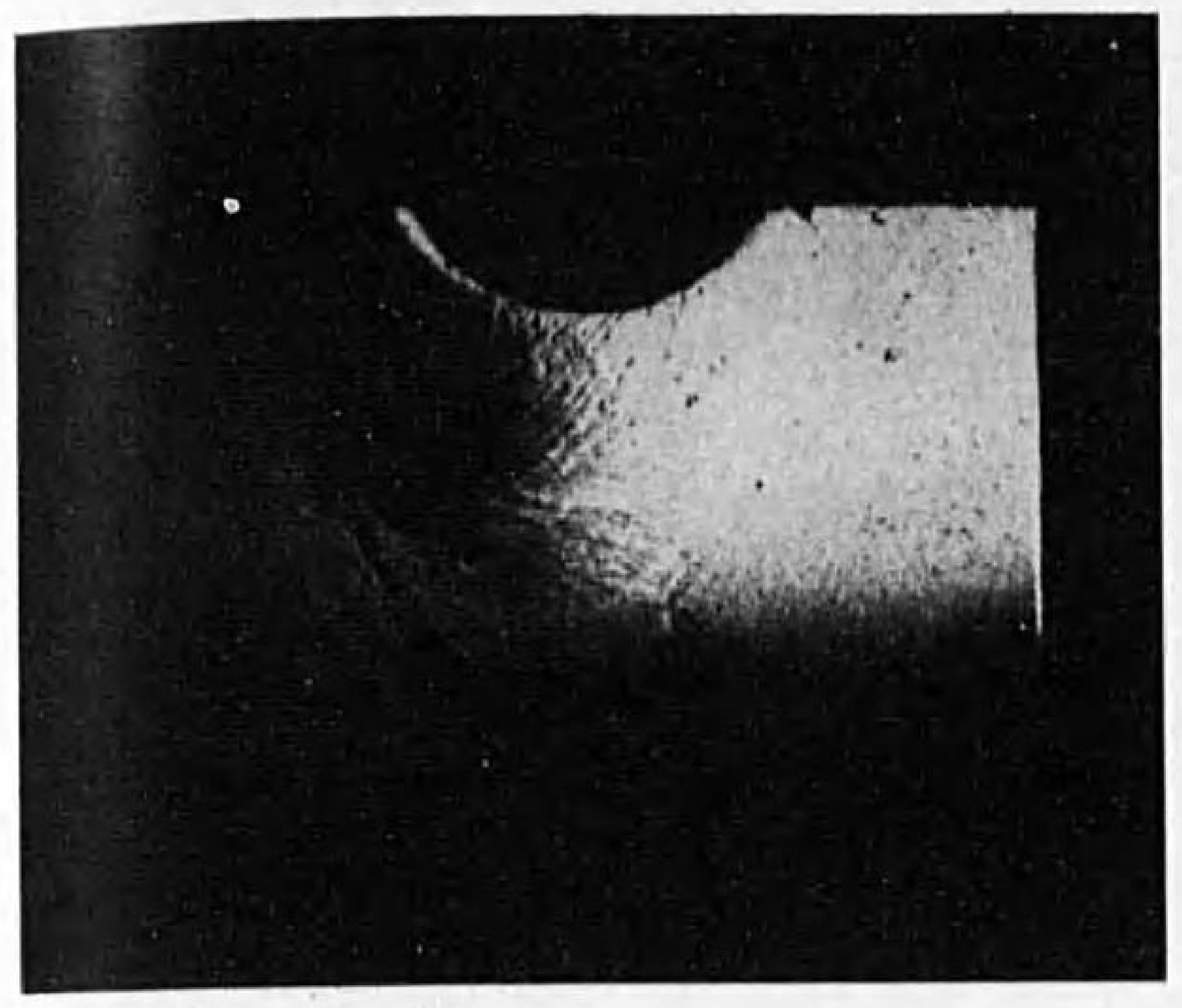

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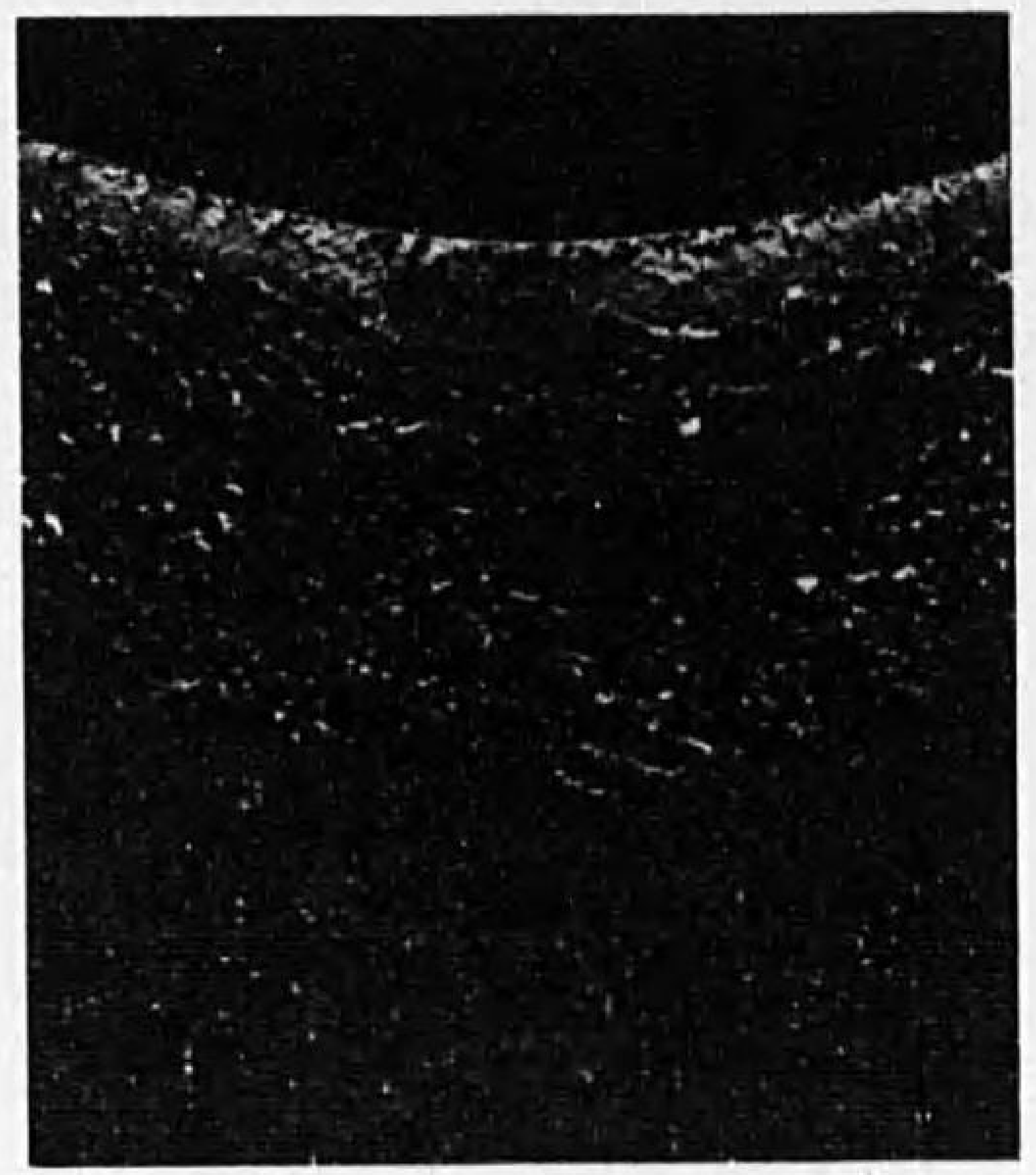

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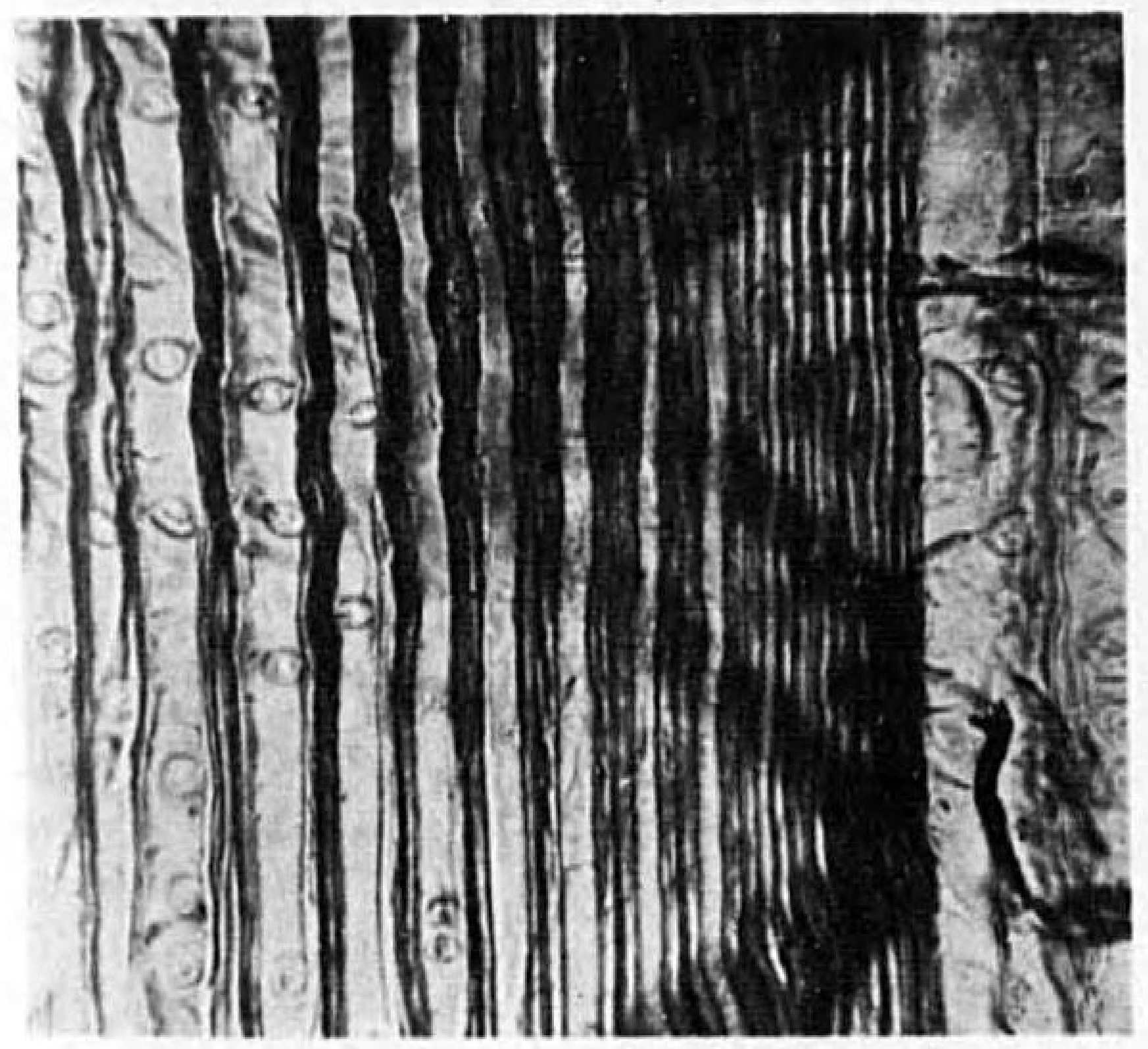

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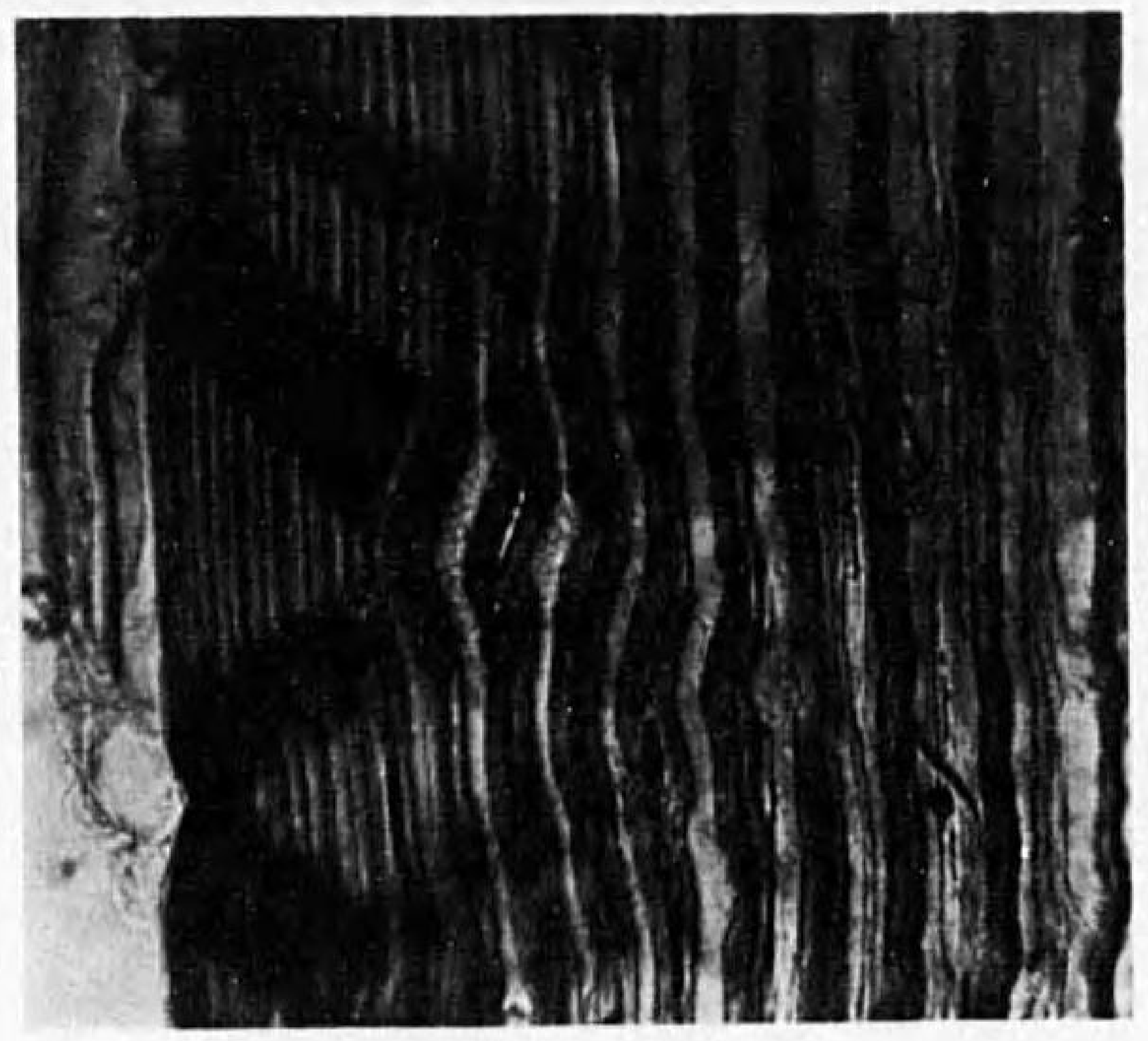
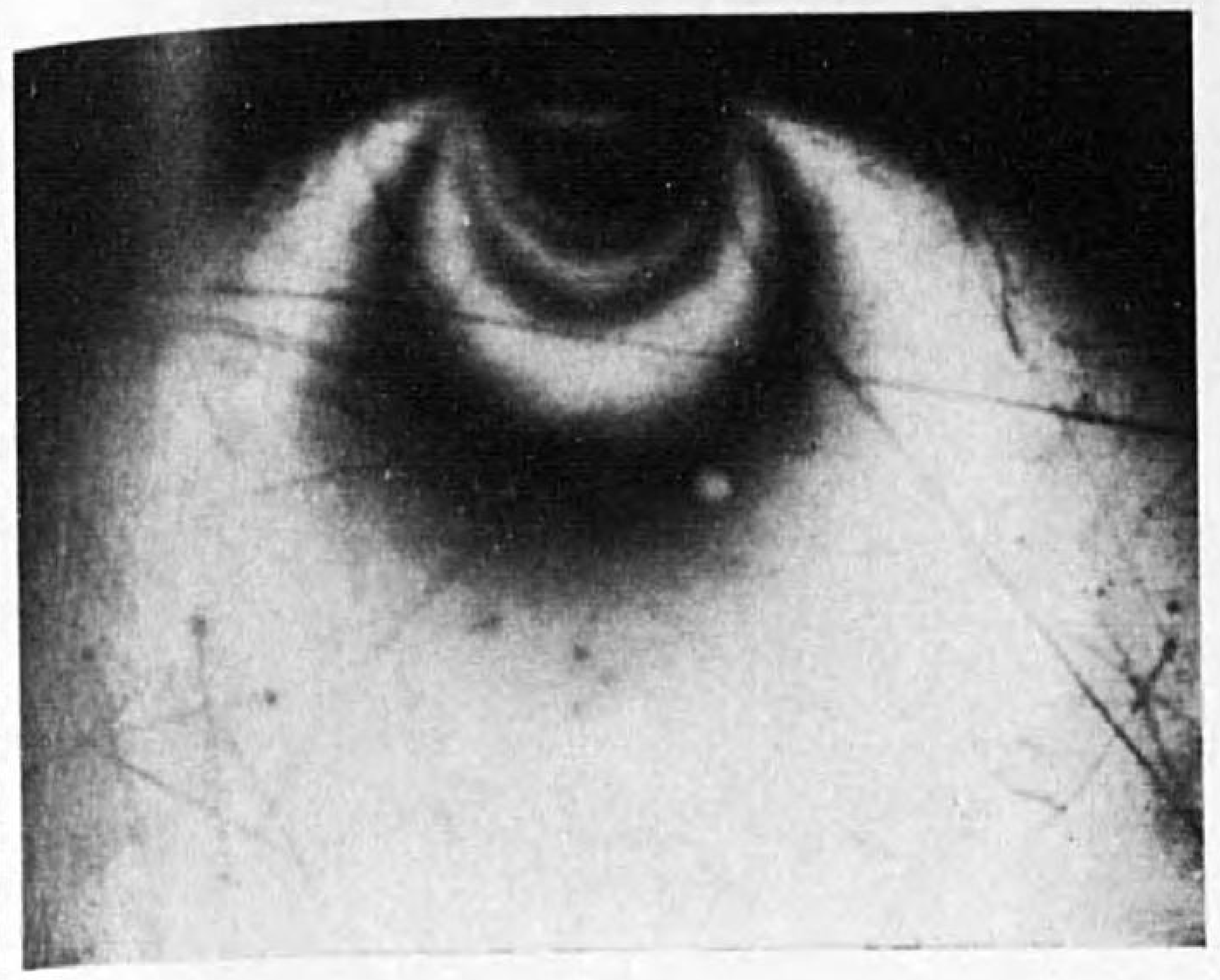


Fig. 24

PLATE V



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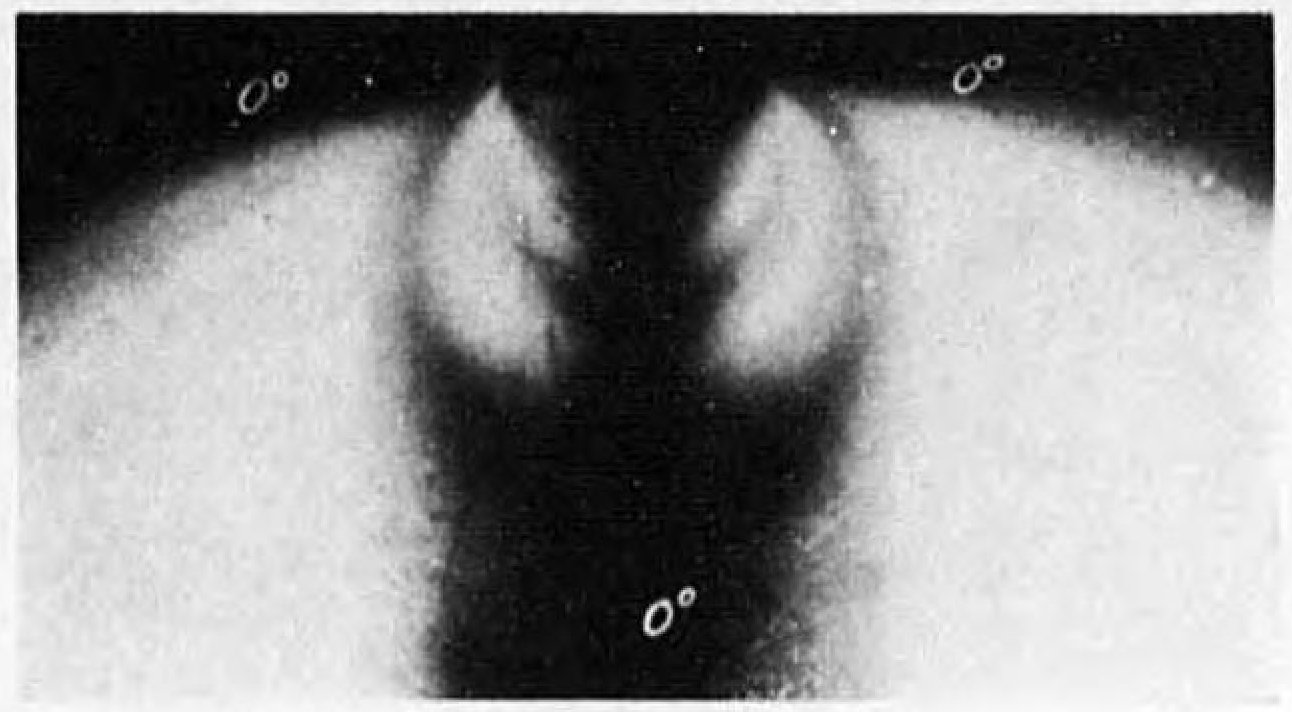

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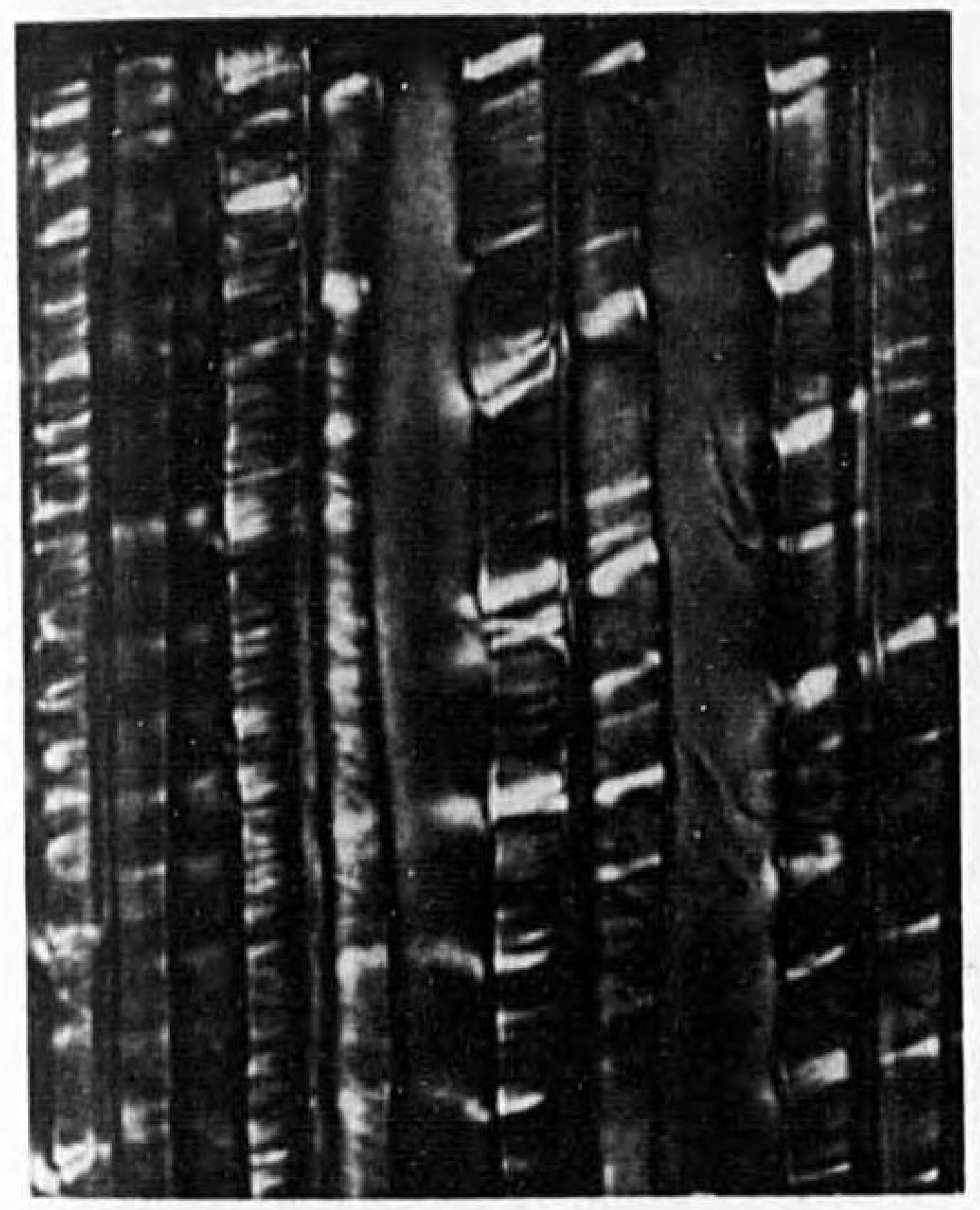
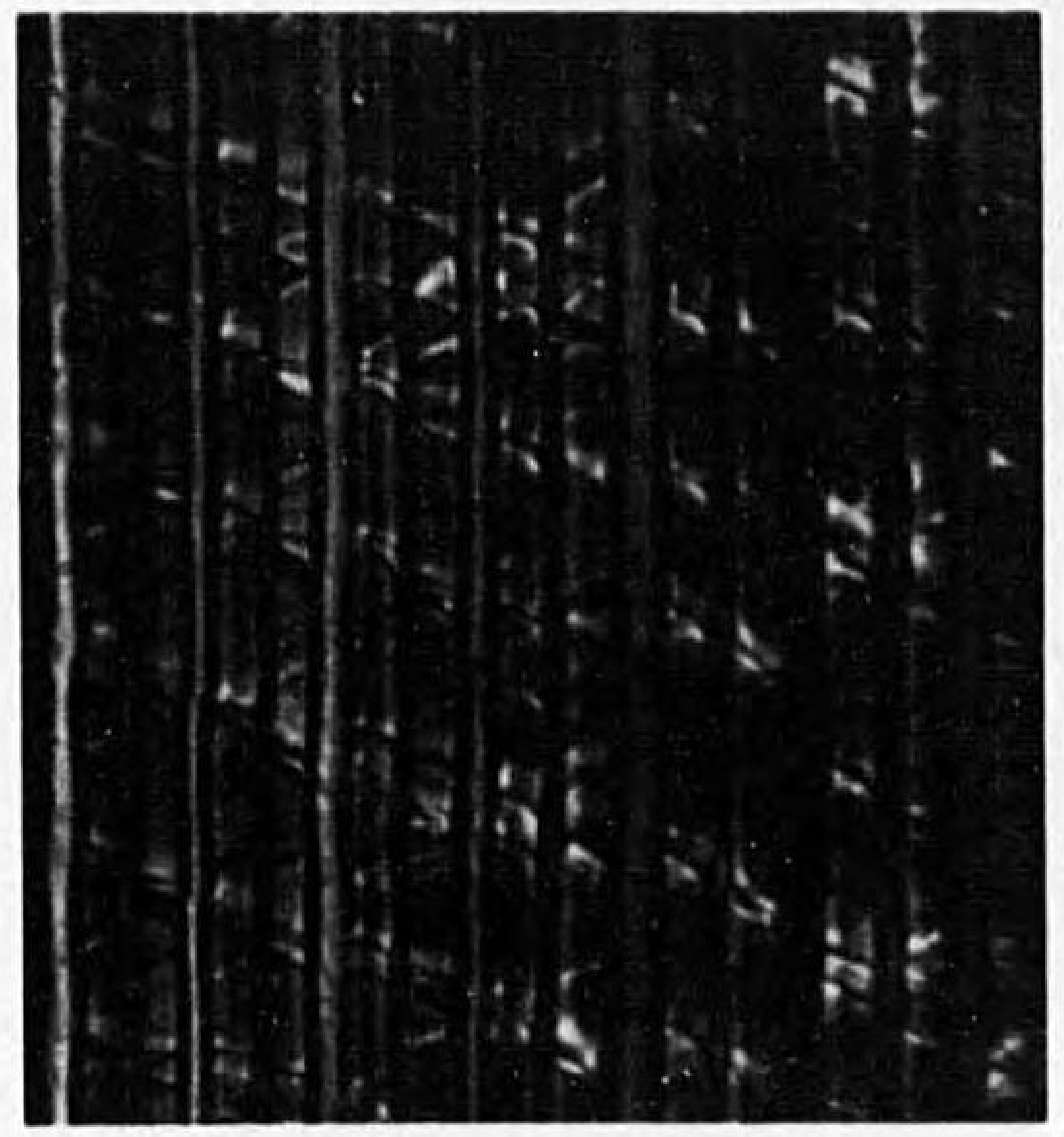


Fig. 27



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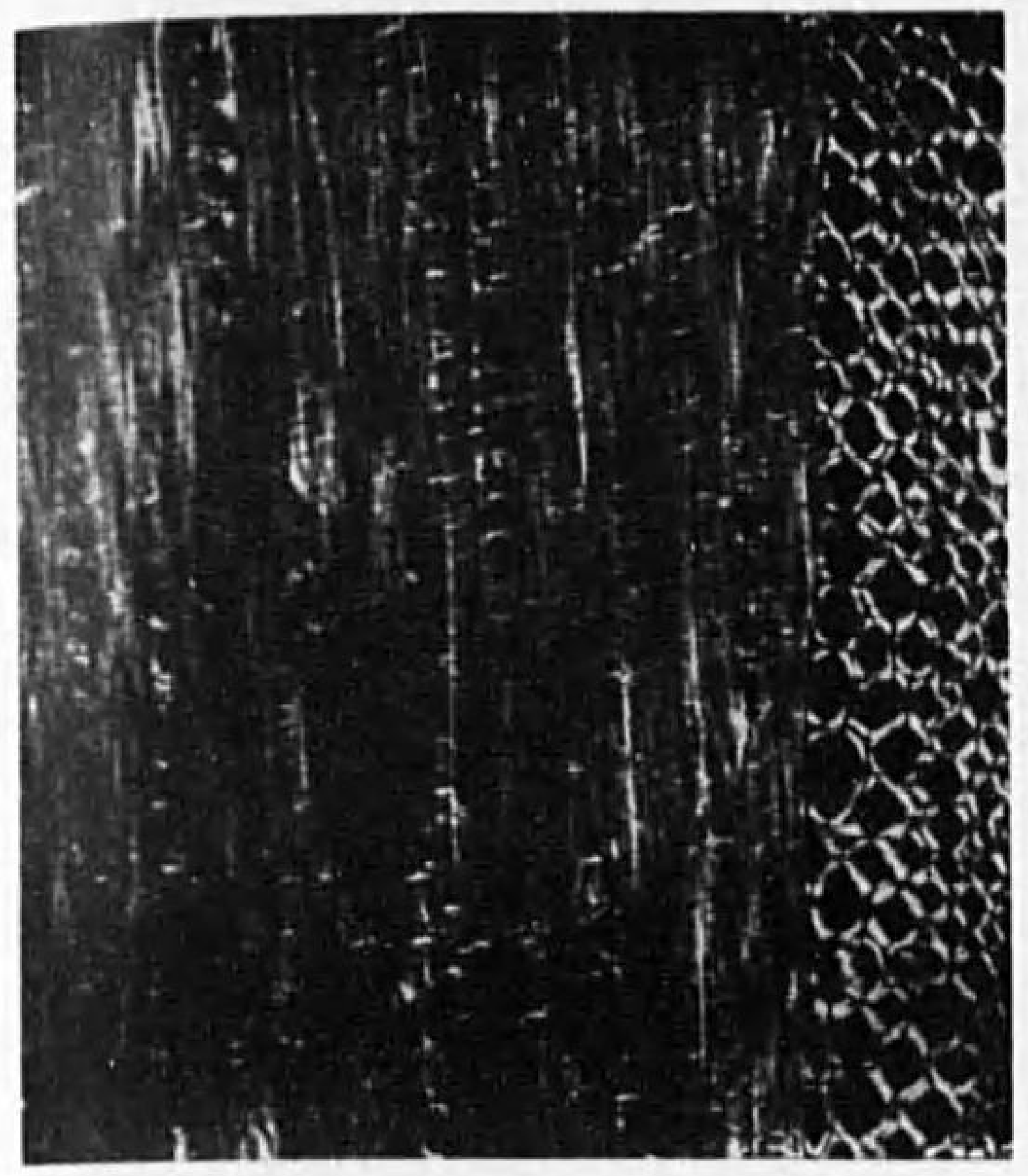

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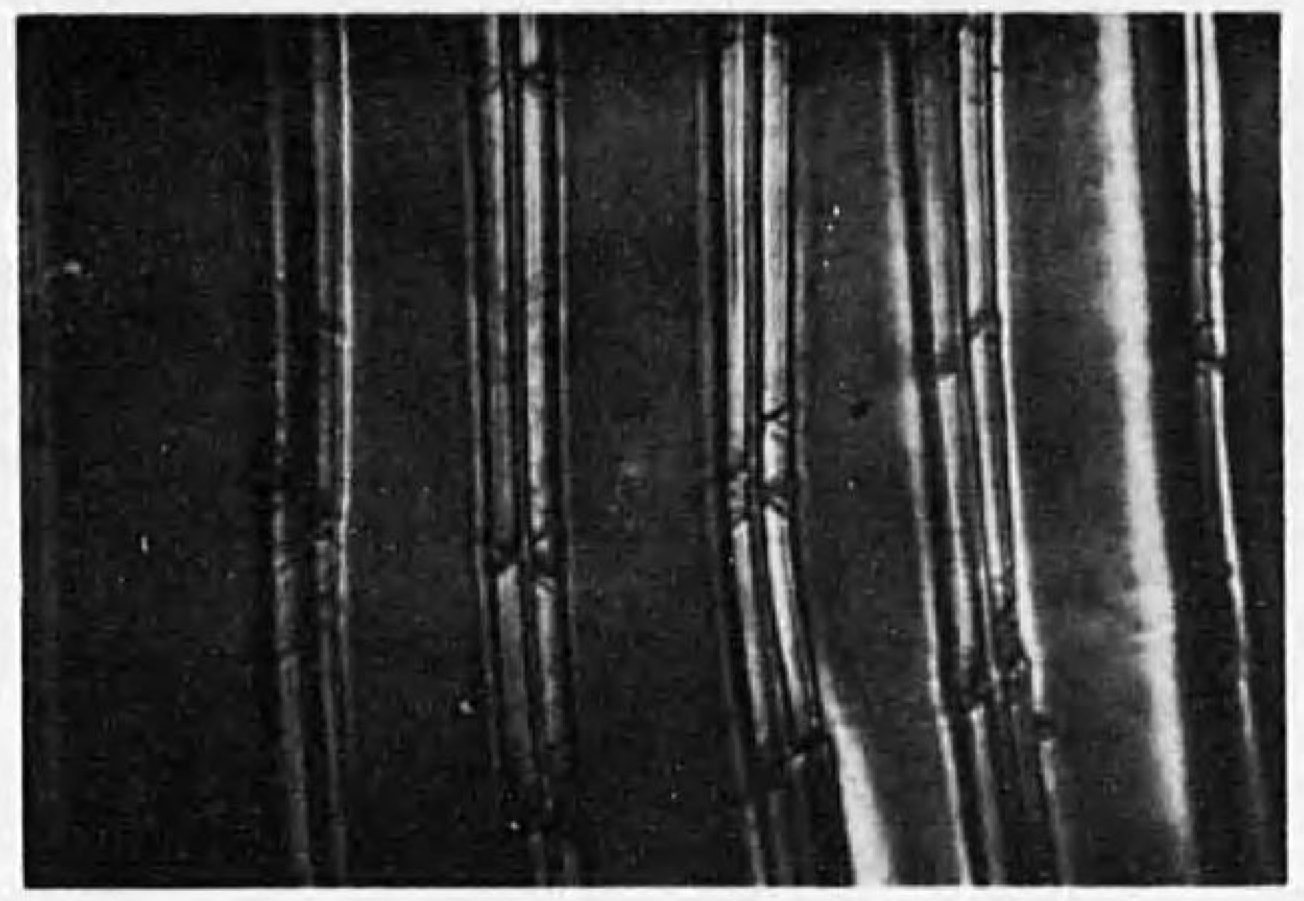

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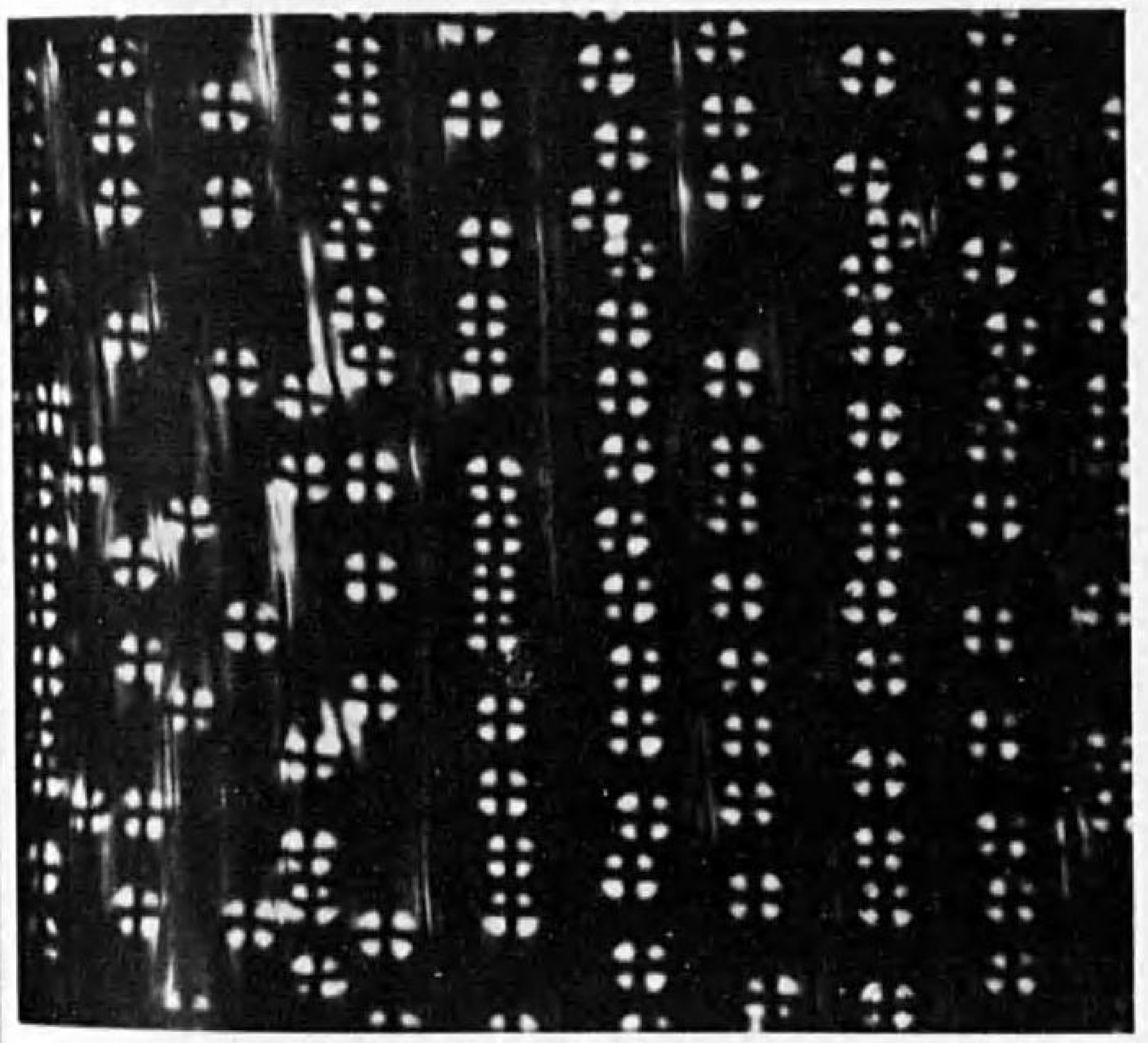

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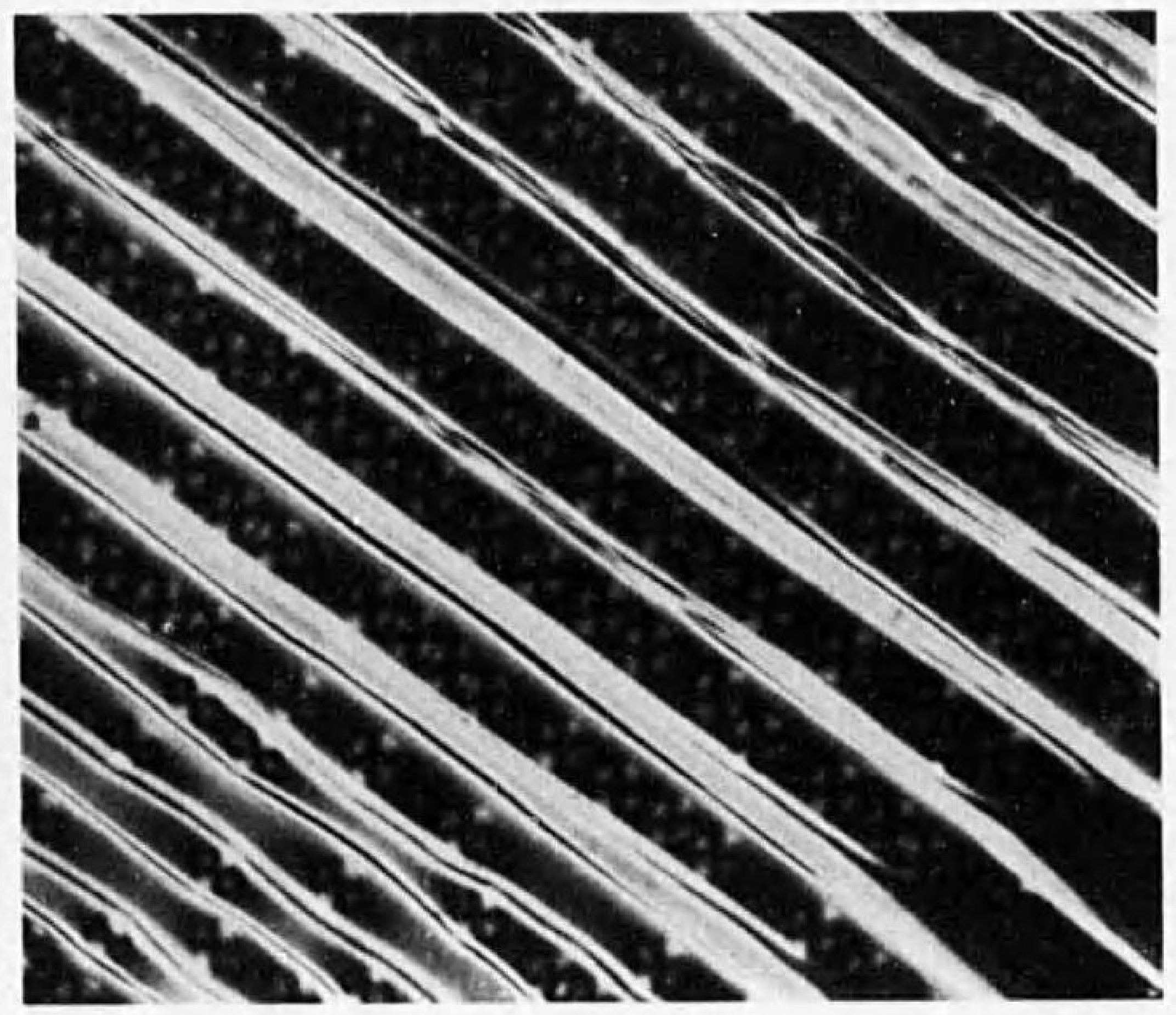

Fig. 32

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