DEPARTMENT OF COMMERCE AND LABOR

TECHNOLOGIC PAPERS

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 11

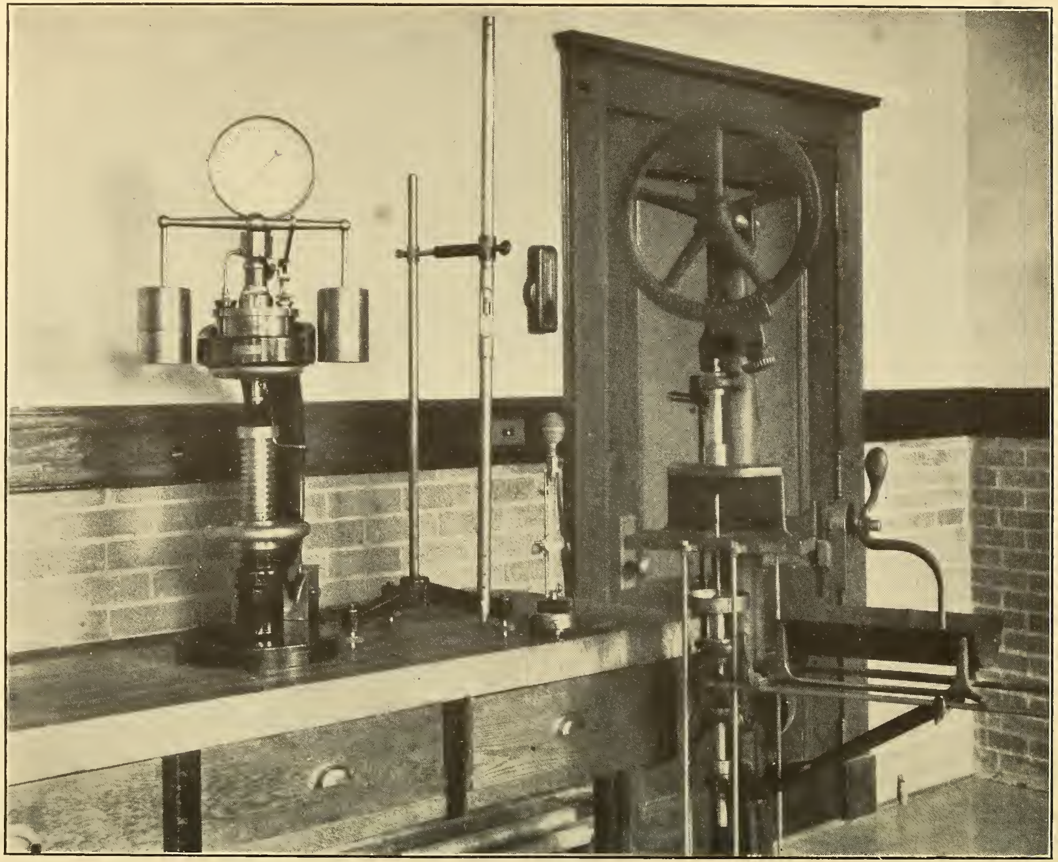
COMPARISON OF FIVE METHODS USED TO MEASURE HARDNESS

BY

RALPH P. DEVRIES, Assistant Physicist
Bureau of Standards

[JULY 22, 1912]

WASHINGTON
GOVERNMENT PRINTING OFFICE
1912



Brinell Ballantine Shore Keep

Fig. 1.—*Four hardness measuring instruments (the Brinell tester may be used with sphere or cone)*

COMPARISON OF FIVE METHODS USED TO MEASURE HARDNESS

By Ralph P. Devries

CONTENTS

	Page
1. Introduction	3
2. The Brinell test	5
Description of method	6
Elastic deformation of the sphere	9
The relation P=at	12
The cone test	14
3. The Shore sclerescope	19
4. The Bauer drill test	20
5. The Ballantine hardness test	21
6. Discussion of results	23
7. Summary	25

1. INTRODUCTION

To the metal worker, and especially to the user of iron and steel, the hardness of metal, whether it is compression, abrasion, or cutting hardness, is one of its most important properties. The results of hardness measurement depend to some extent upon the kind of stress applied. Thus, by compression hardness we mean the resistance a substance offers to indentation by another body. Abrasion hardness is the resistance offered by a smooth surface to scratching. The resistance which a metal offers to drilling or working in any machine tool is designated as the cutting hardness. The methods of measuring hardness in use at the present time are the result of the growing need for information concerning this property. These methods do not conform to the more or less theoretical definitions which have been proposed at various times. They represent the ideas of men interested in finding a solution to the problem that should conform to the needs of the workshop and to the demands of actual practice.

After looking over the field it was decided to investigate only those methods which seem the most promising and which have recently been developed. It is hoped that the study of hardness measurement may assist in developing a standard method of testing. The object of this investigation is to determine to what extent agreement exists between the results obtained by methods which are apparently in no way related to each other. In this preliminary work no attempt has been made to do more than to obtain comparative results for a series of metals which would be sufficient to show the performance of the individual instruments. Consequently no determinations have been made of the elastic constants or other properties of the metal, such as action under alternating stresses, impacts, cold bending, torsion, tension, or compression, although it is evident from the nature of the problem that these constants and properties are necessary for the interpretation of results.

As early as 1722 Reamur originated a test for hardness which depends upon the principle that a harder metal scratches a softer one. Since that time various forms of sclerometers have been introduced, all of which depend upon this principle. To Brinell we owe the introduction of a method of hardness measurement which can be easily applied and the results of which can be expressed in definite physical units.

Brinell originated this method in 1900 while chief engineer and manager of the Fagersta Iron & Steel Works in Sweden. The method as he developed it is based upon determining the resistance offered to indentation by a hardened steel sphere when this sphere is placed on the material under investigation and subjected to a given pressure. He defined the hardness numeral as the ratio of the pressure on the sphere to the area of the spherical indentation produced.[1]

[1] H. Hertz first defined hardness as the mean pressure which exists at the center of the indentation when the material under test has just reached its elastic limit. This definition he applied only to bodies which have surfaces of such a form that a circular indentation results when they are pressed together. Hertz confined his hardness measurements to glass and similar brittle substances in which the attainment of the elastic limit is denoted by the appearance of a circular fissure around the contact area. Such a fissure does not necessarily denote that the material at the center of the indentation has passed its elastic limit. Hertz has shown that it is impossible to apply his definition to metals, because there are no means of telling when the elastic limit is reached at the center of the indentation. (For the mathematical development of the Hertz equations, see H. Hertz Gesammelte Werke, vol. 1, p. 155 ff., or Annalen der Physik; vol. 14, 1904, p. 153 ff. For discussion of the limitations of measuring hardness according to the Hertz definition, see vol. 51, Zs. des Ver. Deutscher Ingenieur Prüfverfahren für Geharteten Stahl under Berücksichtigung der Kugelform Prüfungs ergebnisse Elastische und Bleibende Form anderungen. R. Stribech; vol. 52, Zs. des Ver. Deutsch. Ingenieur, Unter suchungen über Harte Prüfung und Harte. E. Meyer. C. Bach. Elasticitat und Festigkeit, verlag von Julius Springer.)

Since Brinell proposed this method it has been investigated by Le Chatelier,[2] Leon,[3] Malmstrom,[4] Meyers,[5] and others.

The cone test, which is a modification of the sphere test, was first proposed and investigated by Ludwik. The principle of the method is the same as that of the sphere except that a cone of 90 angular opening is substituted for the sphere.

For the measurement of the workability or cutting hardness of metals Bauer proposed a method which depends in principle on the depth of hole drilled in a given time by a drill running at a constand speed and under a constant pressure.

In 1906 Shore originated a hardness-measuring instrument, the action of which depends on the rebound of a hardened steel hammer when it is dropped upon the substance under investigation.

The Ballantine method depends upon the amount a leaden disk is indented when it transmits through an anvil the energy of a falling hammer to the metal to be tested.

2. THE BRINELL TEST

The Brinell test can be carried out in any machine capable of furnishing and measuring the pressures required to force the sphere into the metal. The apparatus used in this work was manufactured by Aktiebolaget Alpha, of Stockholm, Sweden, and is shown in Fig. 2. Accompanying this instrument is a special microscope which can be used for measuring the diameter of the indentation made by the sphere.

The method of carrying out the test as recommended by Brinell is to indent the metal by a sphere subjected to a pressure of 500 kilograms for the softer and 3000 kilograms for the harder metals. The diameter of indentation is then measured, and from it the depth of indentation is calculated from the formula

$$t = D/2 - \sqrt{D^2/4 - d^2/4}$$

where t is depth of indentation
D is the diameter of the sphere
d is the diameter of indentation.

---

[2] Revue de Métallurgie, 1906, No. 2.

[3] Die Brinellsche Härte probe und ihre praktische Vervendung. Proceedings International Association for Testing Materials, 1906.

[4] Stahl and Eisen, 1907, No. 50.

[5] Untersuchungen über Härte prüfung und Härte. Zeitschrift des Vereines Deutscher Ingenieure, 1907.

The measure of the hardness or hardness numeral was then calculated from the formula

$$\text{H. N.} = \frac{P}{\pi t D}$$

Where P is the entire pressure on the sphere and $\pi t D$ is the area of the spherical indentation.

It has been shown by different investigators that the hardness numeral as thus obtained is dependent on the size of the sphere and the load applied in making the indentation. E. Meyer consequently advised that the mean pressure over the projection of the spherical concavity upon a plane perpendicular to the axis of pressure be taken as the hardness numeral. A. Martens[6] and E. Heyn have suggested as the hardness numeral that load which is required to produce an indentation of 0.05 mm in depth. They measured the depth of indentation directly at both high and low pressures and found that a linear relation existed between the two quantities only at very low pressures. Their work was carried out on special apparatus. The author found it advisable to use a different method to investigate the relation between depth of indentation and load at both high and low pressures throughout a range of 100–3000 kg.

DESCRIPTION OF METHOD

A micrometer microscope reading directly to 0.001 mm was mounted on a stand at a fixed distance from the apparatus. To obtain the depth of indentation the cross hairs were first set upon a fine line on the piston when the test piece had been brought into contact with the sphere. An initial reading was taken. The load was then applied and removed before the second or final reading was made. The difference between the initial and final reading is the depth of indentation of the sphere. The load was removed before taking the final reading so that the compression of the sphere and the different parts of the apparatus lying below the line marked on the piston should not be added to the difference already mentioned. The accompanying sketch, Fig. 2, of part of the apparatus and a typical curve for loading and unloading, Fig. 3, illustrate the method.

[6] Vorrichtung zur vereinfachten Prüfung der Kugel druckhärte und die damit erzielten Ergebnisse Zeitschrift des Vereines Deutscher Ingenieure, 1907.

Fig. 2 shows the piston on which the reference line is drawn. The test piece rests on the head, *r*, which is raised or lowered by the screw. When the test piece has been brought into contact with the sphere the desired pressure P is applied. The piston moves downward a distance equal to the depth of indentation, plus the amount of compression of the sphere and the piston. In Fig. 3 this distance is denoted by OR. When the pressure is released the piston does not return to its original position, but to a point indicated by S on the curve of unloading. The distance OS is then the depth of indentation. It is equal to OR, the entire travel of the piston minus SR the compression of the sphere and piston.

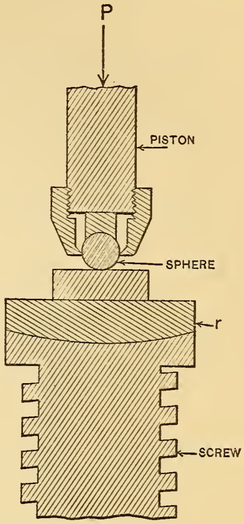


Fig. 2.—*Section of part of Brinell hardness tester*

It was found difficult to bring the test piece into contact with the sphere without indenting it and applying a small initial load. The method used in measuring the depth makes it necessary that the sphere shall begin to indent the metal as soon as the piston begins to travel downward. A small initial pressure was therefore applied before taking the initial reading of the microscope. When

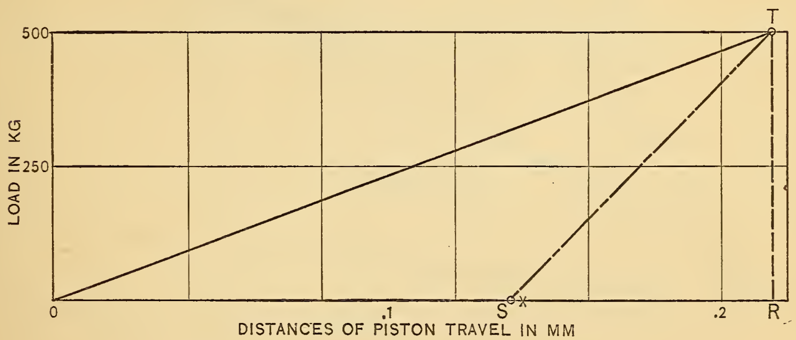


Fig. 3.—*Typical curve of loading and unloading*

the load was released, it was released not to zero, but to the initial load. By releasing the load to zero and bringing it back to the initial load the measurement of the depth of indentation checked to 0.001 mm.

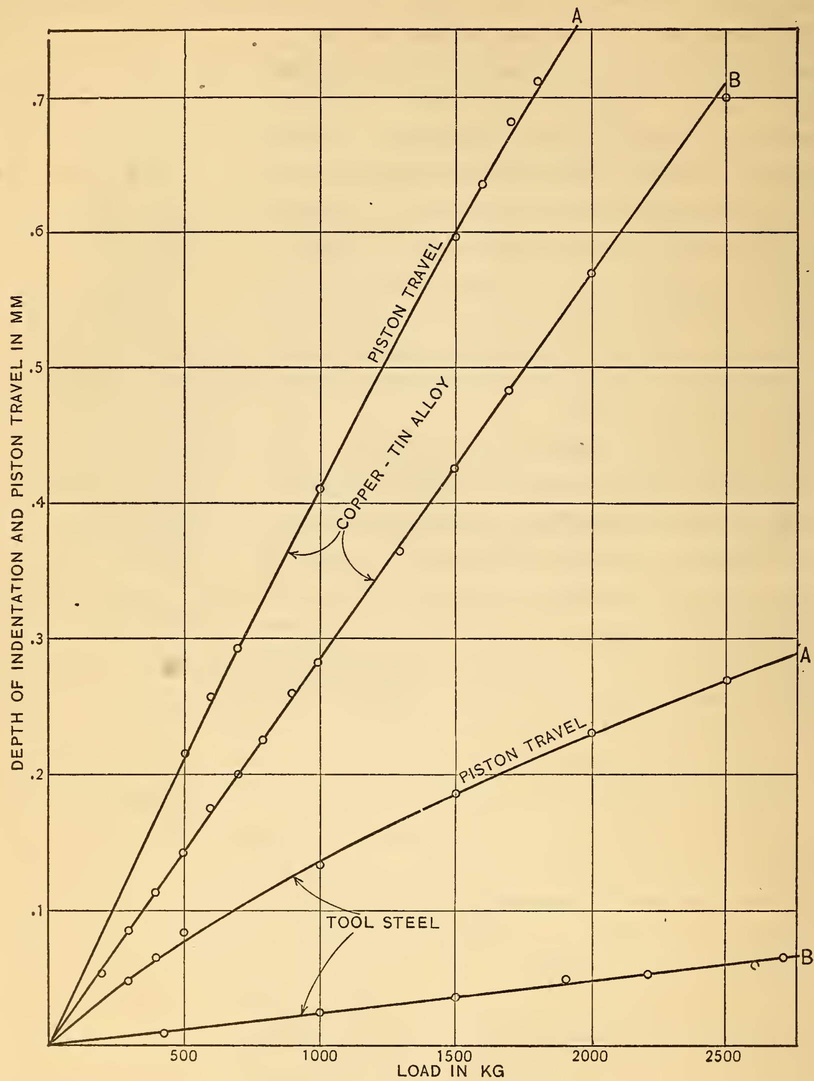


Fig. 4.—*Load-depth relation for two metals*

The total downward travel of the piston was measured for several metals. These results are shown in Fig. 4. The actual depth of indentation as measured is also plotted for easy comparison.

Curve A shows the total downward travel of the piston. Curve B is the actual depth of indentation. The difference between any ordinate of curve A and B represents the compression of the different parts of the apparatus lying below the reference line. Any measurement of the depth of indentation must totally exclude these elastic compressions. It seems probable that Martens and Heyn may have encountered difficulties in doing this, because they state that when their curves deviated from a straight line some of them curved upward and some downward.

The depths of indentation of ten different metals were measured at various loads. These metals ranged from very high carbon steels to metals as soft as copper and aluminum. They were subjected to no special heat treatment and very little was known of their composition. That any single measurement of depth did not give identical results on different parts of the same bar for the same pressures was rather to be expected.

The load was held constant during 15 to 30 seconds, respectively, for the harder and softer metals.

This time was found sufficient to establish equilibrium between pressure and resistance for all of the metals tested. In Fig. 5 the results obtained are plotted. These results show the existence of a linear relation between load and depth of indentation for all pressures from zero to three thousand kg.

ELASTIC DEFORMATION OF THE SPHERE

Since the hardness numeral as ordinarily calculated is a function of the diameter of the sphere, it is necessary to study the behavior of the sphere under compression. A specially prepared bar of Bessemer steel was used for this purpose. This bar was subjected to a temperature of 860° C. for one hour in an electrically heated furnace. It was then cooled to room temperature in eight hours. The depth and diameter of indentation made by loads ranging between 200 and 3000 kg were accurately measured.

It is sometimes difficult to measure the diameter of an indentation accurately, because the line of demarcation between indented and unindented metal is not always well defined. In the case of the softer metals it is far from being circular.

The special steel bar and most of the harder metals showed a well-defined bounding edge and the diameter of indentation was therefore easily measured. The measurements obtained on the steel bar are plotted in Fig. 6.

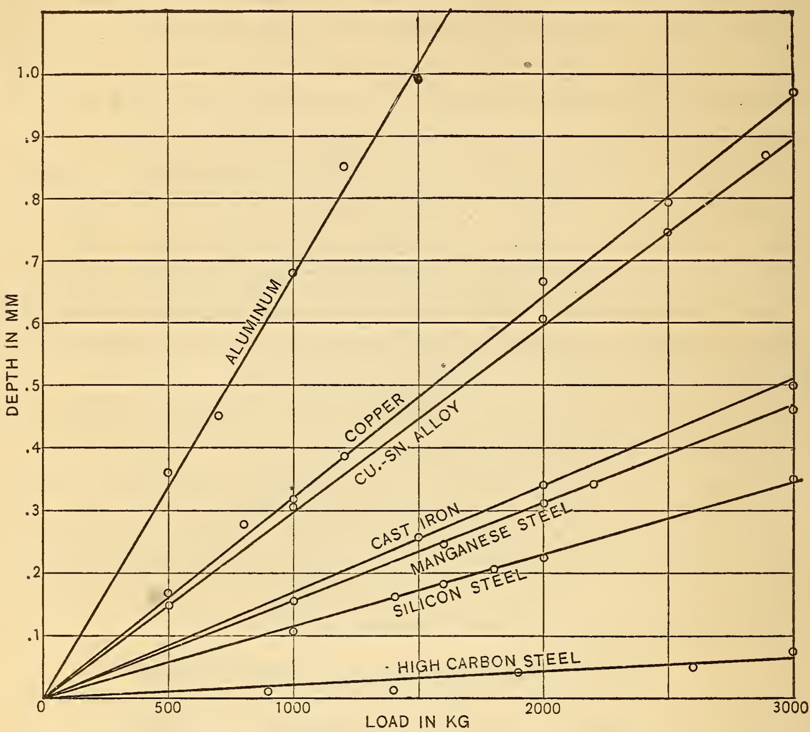


Fig. 5.—*Relation between load and depth of indentation in the Brinell hardness test*

If the steel sphere is not elastically deformed under pressure, then the value of the radius calculated from the geometrical relation

$$R = \frac{d^2}{8t} + \frac{t}{2}$$

should check in every case with the known value of the radius. But if the sphere is elastically deformed, values thus calculated will give approximately the radius of curvature of the indentation. The indentation is actually a segment of a spheroid, but for the small indentations no appreciable error is introduced in assuming it to be spherical. The values of the radius of curvature as calculated from the values shown in Fig. 6 are placed in Table I. The elastic deformation of the sphere is seen to be appreciable for this steel. The radii of curvature obtained for different metals are also placed in Table I for easy comparison.

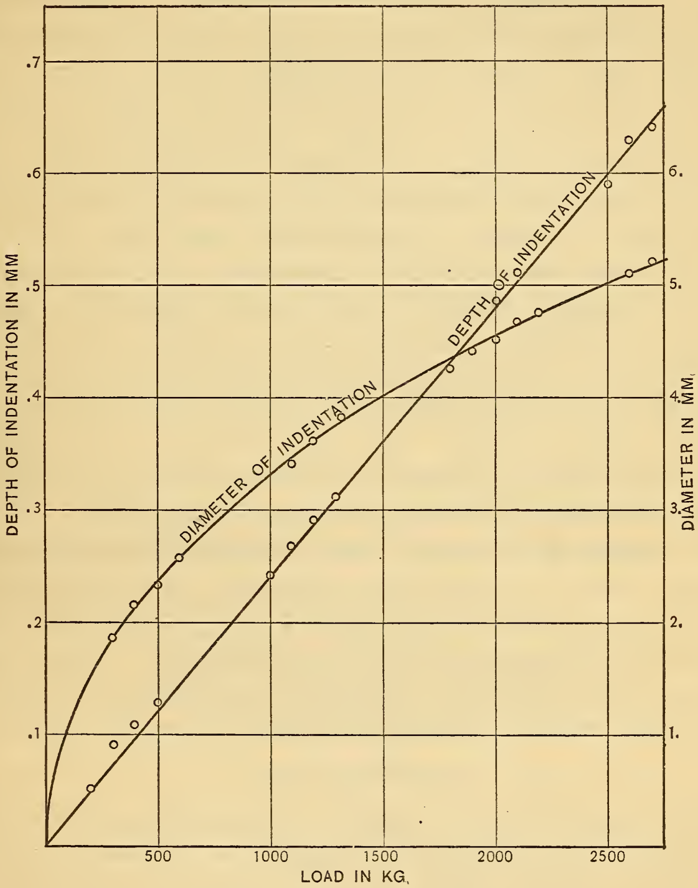


Fig. 6.—*Depth-dia. Load curves for Bessemer steel bar*

These particular metals were selected because they represent different indentation phenomena. The cast iron and bessemer steel, when subjected to pressure formed a ridge about the sphere by flowing up from beneath the sphere above the original surface of the metal. The manganese steel showed no ridge formation, while the tobin bronze and copper vanadium alloy showed a negative ridge formation; that is, the metal near the circular edge was drawn in below the original surface.

For those metals which form a positive ridge the diameter of indentation measured is greater than the true value which corresponds to the measured depths of indentation. The radii of curvature of bessemer steel and cast iron is therefore greater than their true value. That of the manganese steel is correct, while the radii of curvature of the tobin bronze and copper vanadium alloy are less than their true values. The results of Table I, however, show that the radius of curvature is greater than the radius of the sphere for all of the five metals, and that the deformation of the sphere is relatively greatest at the lowest pressures.

At the lower pressures, when the sphere begins to indent the metal, the resistance offered is in the direct line of the applied pressure. The lateral component of the resisting force is then practically zero. As the depth of the indentation increases the effect of the lateral component of the resisting force tends to make the sphere retain its shape. The values of Table I show that the effect of the lateral component of the resisting force tends to decrease the radius of curvature under increasing loads.

Measurements of the sphere before and after loading show that the sphere was not permanently deformed. It is interesting in this connection to note that E. Meyer found practically no elastic deformation of the spheres which he worked with. This is probably due to the fact that he measured the diameter of sphere in the equatorial zone at right angles to the line of applied pressure.

The Relation $P = at$

When we consider that the sphere is always elastically deformed, the calculation of the hardness numeral as advised by Brinell retains no significance unless we replace D in the formula $P/\pi tD$ by the diameter of the sphere, of which the indentation forms a segment.

E. Meyer suggested that the mean pressure, Pm, equal to load divided by the area of projection of the spherical concavity be used as the hardness numeral.

But the relation between the load P and the diameter of indentation is not a simple one. $P = ad^n$ in which a the load required to produce an indentation of 1 mm in diameter, and n are constants that vary with every metal. Only when $n = 2$ does the hardness numeral become independent of the load. In none of the metals tested in this investigation was n exactly equal to 2. For purposes of comparison it will not do to arbitrarily take the hardness at 3000 kg, because E. Meyer has shown that for some metals the maximum hardness has already been attained at this load. For others it has not yet been reached.

The linear relation between load and depth of indentation suggests at once as the measure of hardness, that load which is required to produce an indentation of 1 mm in depth. In the formula $P = at$, a is a constant. It is the load required to produce an indentation of 0.1 mm in depth if t be expressed in tenths of mm. To use 0.1 mm would be preferable to one millimeter, for most of the indentations are less than one millimeter in depth. The values of a for the different metals are placed in Table V.

In order to have a more definite basis for comparison with the cone test the hardness numeral is also calculated on the basis of entire pressure P divided by area of spherical concavity.

Expressed in symbols, $\text{H. N.} = \dfrac{P}{2\pi t R'}$ . . . . (1)

where R' is the radius of curvature of the indentation. For the softer metals the hardness numeral is calculated for 500-kg pressure. This was done in order to avoid inaccurate measurements of the diameter of indentation. The hardness numeral of the harder metals was calculated for the load 3000 kg, because the depths of indentation are so small that an appreciable error would be introduced by a small error in measurement. If the value $P = at$ is substituted in equation 1 it becomes $\text{H. N.} = C/R'$ . . . . (2)

where $C = a/2\pi$

The product of H. N. and radius of curvature is a constant for all loads up to 3000 kg. Since the radius of curvature decreases with increasing loads the hardness numeral must increase. The values placed in Table II show the variations of the hardness numeral for the different loads. The deformation of the sphere has therefore a very important bearing on the results of sphere hardness tests.

If the value of R′ is substituted in equation 1 it becomes H. N. =

$$P/\pi\left(\frac{d^2}{4}+t^2\right) \quad (3)$$

The hardness numeral suggested by E. Meyer is

$$\text{H. N.} = \frac{P}{\frac{\pi d^2}{4}} \quad (4)$$

It can be seen by comparing equations 3 and 4, that they will give practically the same results for low loads, but at the higher loads equation 4 will give hardness results that are much higher than those obtained by equation 3. The variation of the hardness numeral with the load is greater when it is calculated upon the projected area of the indentation than when calculated on the actual area of the indentation. Since equation 2 shows that the product of hardness numeral and radius of curvature is constant for a sphere 1 cm in diameter some measurements were made with a sphere 1.2 cm in diameter. The relation obtained between load and depth of indentation for several metals is plotted in Fig. 7. The hardness numerals $\frac{P}{2\pi t R'}$, are also placed in Table II. These values show a good agreement. It is not improbable that the hardness numeral is independent within certain limits of the size and hardness of the sphere.

THE CONE TEST

The sphere and cone test are both modified forms of a compression pressure test and can be carried out in the same apparatus. Ludwik[7] seems to have been the first to propose and use this test for hardness. He measured the depth of indentation by means of a device, the action of which depends upon the downward motion of the piston. The area of the conical indentation was calculated from the values of the depth of indentation. The hardness numeral was then computed by dividing the pressure by the area of the indentation.

[7] Die Kegelprobe: Ein neues Verfahren zur Härte bestimmungroon Materialen Verlag von Julius Springer.

Much has been claimed for the cone form of hardness test in preference to the sphere, the principal claim being that the circular cone makes indentations which are geometrically similar for differ-

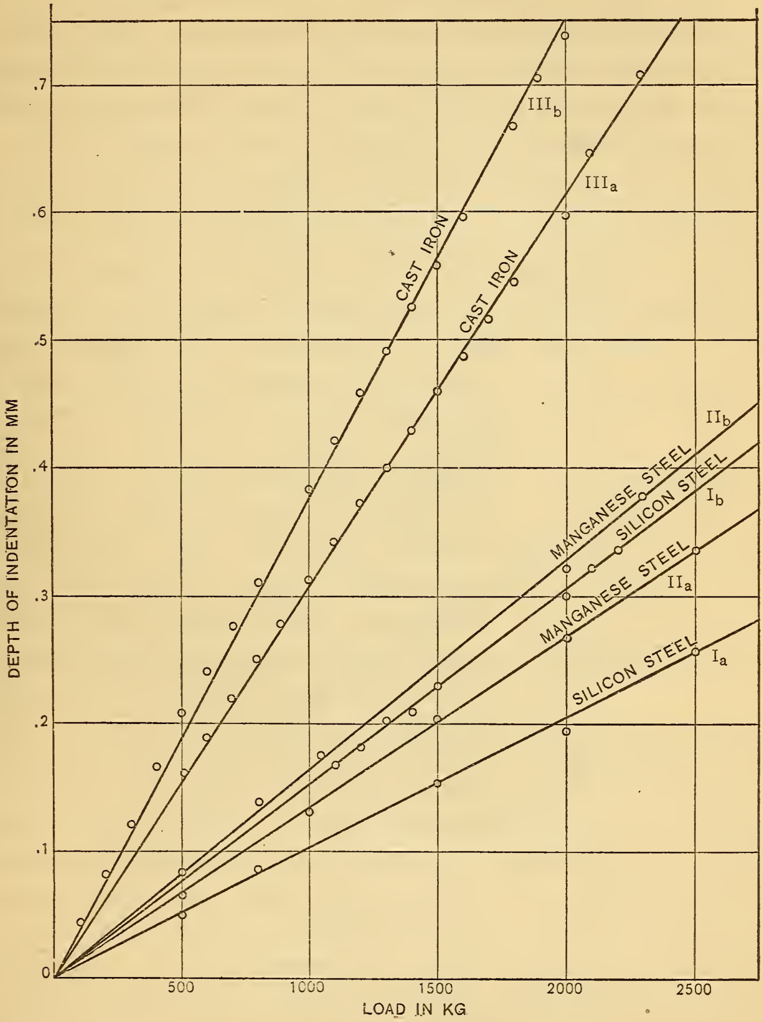


Fig. 7.—*Load-depth relation for spheres of different diameters*

ent pressures. Since the variation in the hardness numeral for different loads in the sphere test is due to the fact that the indentations are not geometrically similar, it was decided to carry out tests with cones of 60° and 90° angular opening.

All of the metals previously tested by the Brinell method were tested with cones of 60° and 90° angular opening. The depths of indentation were measured in the manner described in the sphere test. The depth of indentation was measured because it is the only dimension that can be accurately measured. The diameter of the indentation might be measured if it were not for the fact that the metal when under pressure flows up above the original surface of the metal forming a ridge about the cone, as shown in Fig. 8.

E. Meyer has pointed out that this ridge of metal supports part of the applied pressure and that the calculation of the hardness numeral as carried out by Ludwik is incorrect. He says in substance that if the hardness numeral is calculated from the formula H. N. = .225 $^{P}/t$ that it will be too large in value, since t as measured is not the true depth of indentation. He suggests that instead of measuring t (see Fig. 9), d be measured and t' calculated from it. Using t' instead of t in the above formula would then give a value for the hardness numeral which would accurately represent the resistance to indentation. Meyer in his own work measured d and calculated the hardness numeral on the basis of the entire pressure divided by the projection of the conical indentation on a plane at right angles to the axis of pressure. That either of these methods which he advised as corrections have any advantage over the method proposed by Ludwik is extremely doubtful. He assumes that the ridge of metal offers as much resistance to indentation as if it were solid metal with unstressed metal all around it. The metal which forms the ridge flows up from beneath the cone. It may safely be presumed that in doing so it has lessened the resistance to indentation of that part of the metal, so that if this effect could be measured the correction would probably have to be applied, but with the opposite sign. Moreover the amount of ridge formation for a given pressure depends upon the metal itself. It is attendant upon the test performed as much as the decrease of cross section of a tensile specimen for a given stress is dependent on the nature of the metal.

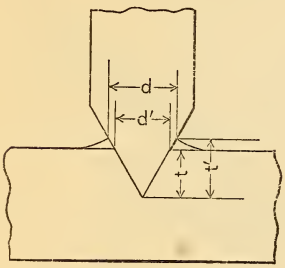


Fig. 8.—*Cone ridge formation*

In Fig. 9 the depths of indentations for various loads are plotted for several metals. If the relation between load and depth of indentation is a parabola, as would seem, then $P = at^n$, which may

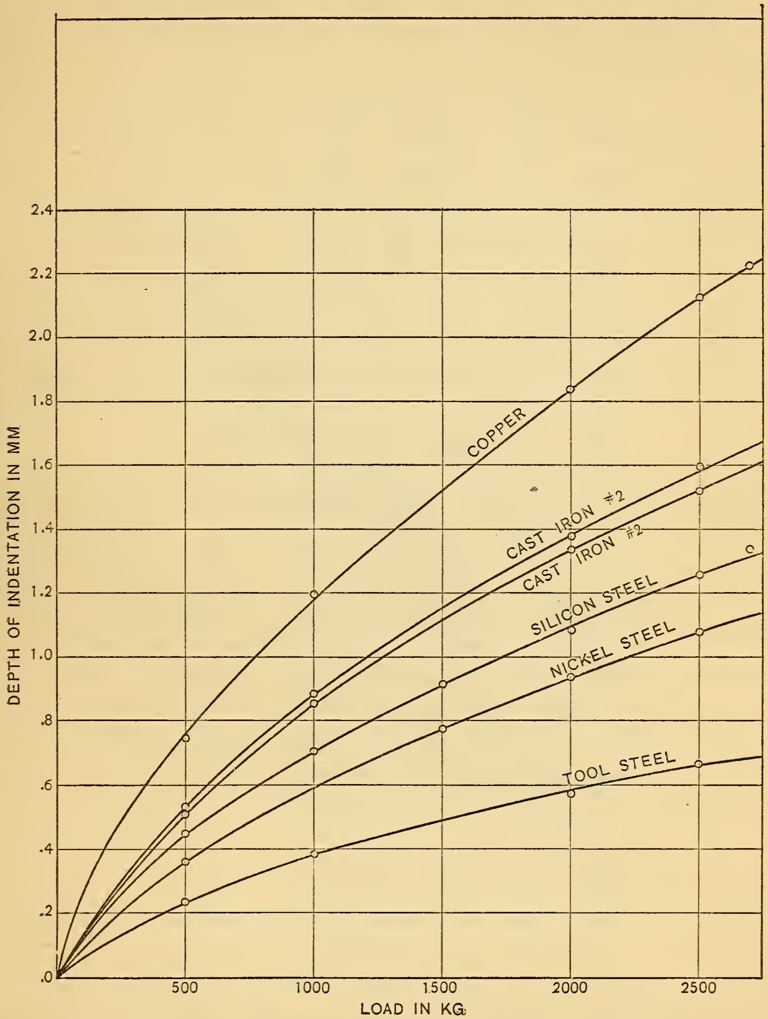


Fig. 9.—*Relation between load and depth of indentation in the cone test*

be expressed as $\log P = \log a + n \log t$. In Fig. 10, the relation of $\log P$ to $\log d$ is plotted for the metals of Fig. 9. Since the relation is a linear one the relation between load and depth of indentation is expressed by $P = at^n$. The value of n and a can be determined directly from the curves of Fig. 10. Some of the results which Ludwik gives in his paper are tabulated in Table III. The same table also contains the results as obtained in this investigation. The difference in the hardness numeral is easily seen to be

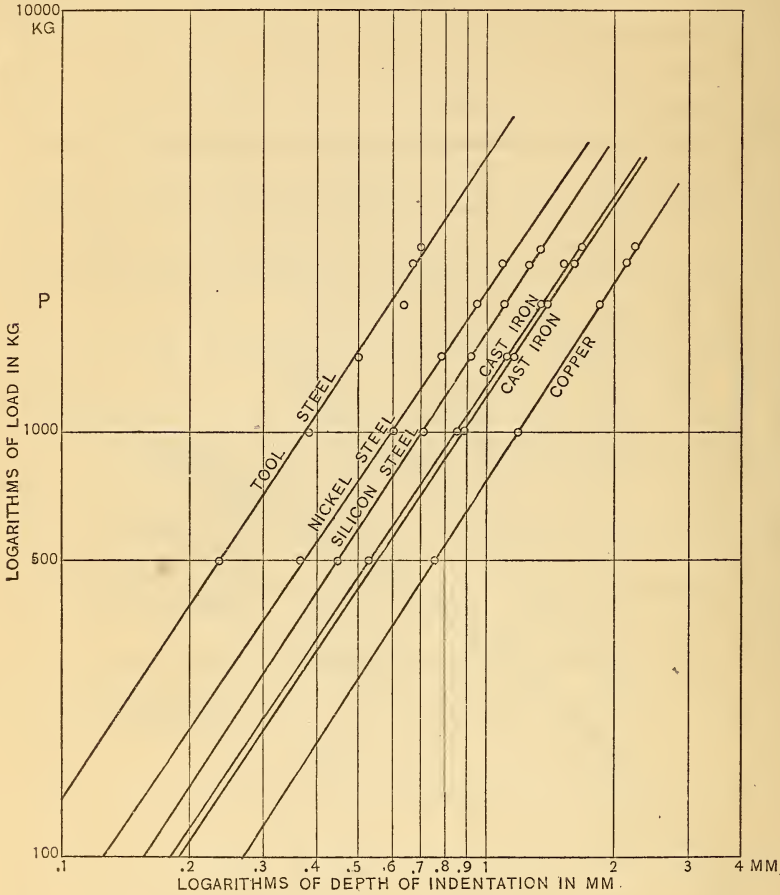


Fig. 10.—*Curves Log $P = \log a + n \log t$ for the cone test*

due to the difference in the depths of indentation obtained. If these values of Ludwik's for the hardness numeral were correct, it would not be necessary to assume any particular load at which to calculate the hardness numeral. But the facts are that the hardness numeral decreases rapidly with increasing load. Ludwik seems to have been aware of the errors which exist in his measurements, for in a footnote he remarks that by making more careful measurements of the depths of indentation, the hardness numeral would decrease with increasing loads. He also states that the hardness numeral would have to be calculated at the higher loads; that is, at those loads where the depth of indentation changes only slightly with increase of load.

The hardness numeral has, therefore, been calculated for the load of 3000 kg. The results obtained are entered in Table V. For two grades of steel it was impossible to obtain results for the cone test, because the cones were appreciably blunted by the steel. Even in the case of the softer metals the cones become blunted after a limited number of tests. This limitation and the fact that the hardness numeral varies with the load shows that the cone test is more limited than the sphere in its practical applications.

3. THE SHORE SCLEROSCOPE

A cut of the scleroscope is shown in Fig. 1. The instrument briefly described consists of a pointed hammer which falls from a definite height through a guiding glass tube upon the metal to be tested. The height to which the hammer rebounds is the measure of the hardness and is read directly from a scale placed back of the glass tube. This scale is approximately 10 inches in height and is arbitrarily divided into 140 equal parts. The hardness numeral is therefore not expressed in definite physical units. This is not a disadvantage if the scleroscope is simply accepted as a hardness measuring device, but it leaves much to be desired for investigational purposes.

In this method of measuring hardness the hammer makes a permanent indentation in the metal under test. An attempt was made, therefore, to determine the hardness as the resistance to indentation. In order to do this, it is necessary to measure either the diameter or the depth of indentation. Both of these quantities are extremely small and the former is inaccessible to all length measuring devices. Some measurements of the diameter of indentation were made, but in general this is impracticable, because the bounding edge of the indentation is not circular. In the measurements referred to the greatest diameter of indentation amounted to only 0.005 mm.

It would be entirely practicable to determine the hardness numeral in the manner outlined if the hammer was enlarged and the height of fall increased so that the diameter of indentation could be measured accurately.

In working with the scleroscope it was found that the hammer must be calibrated after a certain number of tests. For this purpose a piece of steel hardened to 100 scleroscope measurement must be used. The rebound for any given steel can not be corrected by proportionate decrease or increase if the hammer gives a rebound either less or greater than 100 on the hardened steel. This shows that a slight change in the form of the hammer assigns the metal tested to a different position in the hardness scale. Although many things are stated by the inventor concerning the theory of the instrument, which can not be accepted without experimental confirmation, they will be discussed later in the paper which deals with the relations of the physical properties of metals to hardness. The hardness numerals of all the metals tested are entered in Table V.

4. THE BAUER DRILL TEST

The Bauer drill test differs essentially from the other hardness tests. It indicates the cutting hardness and has for its object the determination of the workability of metals. The ease or difficulty with which a metal is worked in any machine tool is known to depend upon the toughness and the abrasive qualities as well as the hardness. The drill test can not, therefore, be considered as being merely a test of hardness.

Since the drill test depends upon other qualities than hardness, it is evident that the results obtained should furnish instructive comparisons.

The machine which was used in this work is manufactured by William Keep and was designed for testing the hardness of cast iron. A cut of the machine is shown in Fig. 4.

The machine has for its essential parts (a) a fluted drill driven at constant speed; (b) a table upon which the metal to be tested is placed and from which weights may be suspended for securing desired pressures; and (c) an autographic attachment which traces a curve whose ordinates are some constant multiple of the depth of hole drilled and whose abscissas represent some constant multiple of the number of revolutions required to drill a given depth. The drill was sharpened on a special grinder in such a manner that the rake and clearance was the same for every test.

The metal to be tested is securely clamped or otherwise held on the table. The weights needed to give the desired pressure are hung on the supports attached to the table. The point of the drill is allowed to drill into the metal before the diagram tracing attachment is thrown into gear. If the drill dulls it becomes apparent at once from the change of slope of curve. The drill must then be taken out and sharpened.

Of all the metals tested by the other methods only a few could be tested by the Bauer method. Some difficulty was encountered even in testing these. This was chiefly due to the fact that they had to be drilled at the same pressures in order to have a basis of comparison. It is a matter of common experience that the pressure applied to the drill and the speed at which it runs must be suited to the metal. Since the method depends upon the rate at which the metal is drilled for the measure of the hardness of workability, it is obvious that the results obtained for different metals are comparable only within very narrow limits.

The line traced by the autographic apparatus shows a linear relation between multiples of the depth of hole drilled and the revolutions required to drill it. The tangent which this line makes with the Y axis is taken as the hardness numeral. For metal as hard as the steel drill the line traced is the X axis. The hardness numeral of such metal is therefore infinity. The results obtained are placed in Table V. Each result is the mean of three separate determinations.

5. THE BALLANTINE HARDNESS TEST

The Ballantine instrument is shown in Fig. 5. Fig. 11 is a sketch of the essential parts of the instrument. The hammer H is fitted with a hardened cylindrical piece of steel E. The two springs s and S' are attached to the hammer and hold a leaden cylindrical disk of 0.6 mm. in depth and 1 mm. in diameter in the position shown. The hammer is held in the upper part of the tube T by a trigger not shown in the figure. The anvil A in the lower part of the tube is free to move vertically.

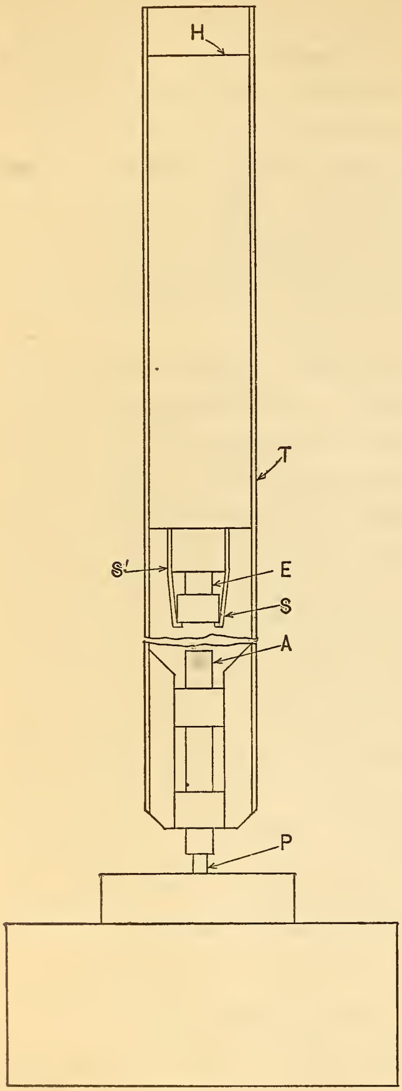


Fig. 11.—*Ballantine hardness tester*

The upper part of the anvil is a duplicate of the lower part of the hammer. The anvil terminates in a point P, which rests upon the metal to be tested.

The instrument is supposed to operate and give results as follows: When the hammer is released it falls on the anvil, and the force of the blow drives the point P into the test piece. The lead disk is then indented a certain amount, depending on the hardness of the metal. If the metal is hard, the disk will be indented more than if the metal is soft. The reciprocal of the depth of indentation of the lead disk is the hardness numeral.

Tests were made on 10 different metals, but the indentations of the lead disk were practically the same for the hardest and softest metals.

The instrument as it comes from the manufacturers has an anvil point which is a circular cylinder slightly upset at the end. Thinking to increase the sensitiveness of the apparatus, anvil points were provided which were circular cones of 120°, 90°, and 60° angular opening, respectively. The results of three copper-tin alloys obtained with these different points are given in Table IV. A comparison of these results shows that the modified cone points did not serve the expected purpose.

The next modification introduced was to reduce the area of the lower end of the hammer and the upper end (F) of the anvil, the area being reduced in approximately the ratio 2:3. That neither of these modifications served the intended purpose is shown by the results placed in Table V.

For all of the metals tested the depth of indentation of the metal (not the disk) was very small, amounting in the case of the softest metal to about 0.3 mm. The energy of fall of the hammer is therefore practically a constant. This energy is spent in indenting the test piece, the leaden disk, and in heat. If a hard metal is tested, the indentation of the metal is small, but the work done may be no less than that required to produce a larger indentation in a softer metal. The experimental results seem to show that there remains only a constant fraction of the energy to do the work required to indent the leaden disk. This fraction of the total energy available can be a varying quantity for the different metals only when the total energy of the falling hammer is itself a variable quantity for every metal. This would be the case only for widely varying depths of indentations of the metal.

6. DISCUSSION OF RESULTS

The hardness numerals for all of the metals tested by the five different methods are entered in Table V. To enable the reader to see at a glance how these methods compare, the results obtained by the scleroscope, the sphere, and the cone method are represented graphically in Fig. 12. To obtain convenient numbers for graphical representation the hardness numeral of the scleroscope is multiplied by 100, that of the sphere $\left(\frac{P}{2\pi t R^1}\right)$ and of the cone are multiplied by 10. The sphere numeral $\left(\frac{P}{t}\right)$ is unchanged.

If the five methods measured the same quantity, the series of ordinates of the points of hardness by one method would be proportionate to the series by any of the other methods. In these curves it is interesting to notice that the widest divergence between the Brinell and the Shore method occurs for those metals which contain elements whose presence is generally supposed to contribute toughness rather than hardness to a metal. Consider, for instance, the copper-tin alloys numbered 1, 2, 3, and 4. Number 1 is an alloy of 90 per cent copper and 10 per cent tin. By the scleroscope it shows a hardness greater than that of tool

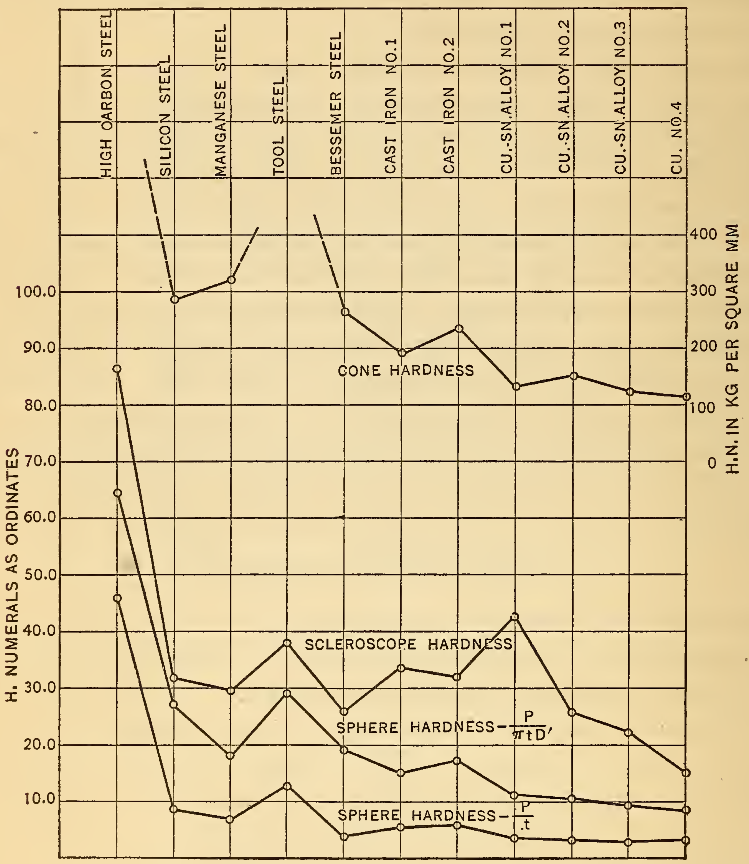


Fig. 12.—*Comparison of hardness numerals of different methods*

steel. By the Brinell test it shows a hardness not much greater than that of ordinary copper commercially pure. Number 2, an alloy of copper 8 per cent and 15 per cent tin, is harder than Bessemer steel or cast iron by the scleroscope. By the Brinell test it is only slightly softer than copper-tin alloy No. 1. By both the scleroscope and the Brinell method the hardness for the copper-tin alloy series is in the same direction. Alloy No. 1 is the hardest, with numbers 2, 3, and 4 following in order. Compare this with the Bauer drill test hardness numerals and we see that the order is reversed. Alloy No. 1 drills the easiest, with Nos. 2, 3, and 4 following in the order named.

The cone and sphere tests give results that are quite concordant throughout. For these two tests a strict comparison can be made, for the results are expressed in the same units.

7. SUMMARY

The various methods for measuring sphere hardness are compared.

A method is given for measuring the depth of indentation which shows the existence of a linear relation between load and depth.

This method makes a rational sphere-hardness scale possible by the determination of one constant.

The effect of elastic sphere deformation on the hardness numeral is determined.

Cone-hardness numerals are determined by depth measurements. The results show that the law of similarity is not fulfilled in the cone test.

The cone test is also shown to be more limited in its practical applications.

The scleroscope hardness results are not in good agreement with the Brinell tests for the harder metals, and the lack of agreement is more noticeable for the alloys of the softer metals.

The Keep drill tests show that cutting hardness depends on a different property of a metal than resistance to indentation.

TABLE I

Radius of Curvature of Indentation for Different Metals

Load, in kg	Values of R', in cm for—				
	Bessemer steel	Cast iron	Tobin bronze	Copper vanadium alloy	Manganese steel
500	5.71	6.71	6.31	6.72	7.64
1000	5.79	6.46	5.83	6.46	6.98
1500	5.73	6.26	5.43	6.26	6.59
2000	5.59	6.16	5.13	6.16	6.24
2500	5.56	6.05	5.05	6.05	5.70
3000	5.57	5.91	5.06	5.91	5.43

TABLE II

Values of Hardness Numerals Obtained with Spheres of Different Diameters

Load, in kg	Hardness numeral							
	Copper for—		Manganese steel for—		Silicon steel for—		Cast iron for—	
	1.2-cm sphere	1-cm sphere	1.2-cm sphere	1-cm sphere	1.2-cm sphere	1-cm sphere	1.2-cm sphere	1-cm sphere
1000	86.5	83.4	179	177.5	215	214	136	137
2000	....	....	183	181.5	222	219	138	139
3000	....	....	187	185.6	225	225	140	144

TABLE III

Comparison of Results for the Cone Hardness Test

Load, in kg	Ludwik's data for copper: "t" in mm	H. N.	Author's results: "t" in mm	H. N.	Ludwik's data for "t" in mm	H. N.	Author's results: "t" in mm	H. N.
500	1.23	74.4	0.759	195	0.93	130	0.549	374
1000	1.74	74.3	1.201	154.9	1.32	129	.864	304
1500								
2000	2.46	74.3	1.844	132.0	1.85	132	1.343	256
2500	....	....	2.139	122.8	2.27	132	1.523	242
3000	3.00	75.0	2.435	114.0	2.27	131	1.683	239

TABLE IV

Depth of Indentation for Different Cone-Pointed Anvils in the Ballantine Test

Metal	Depth of identation in lead disks for circular cone anvils of—		
	120°	90°	60°
Cu.-sn-alloy 1	3. 26	3. 14	2. 99
Cu.-sn-alloy 2	3. 20	3. 35	3. 04
Cu. 4	3. 18	3. 17	2. 95

TABLE V

Hardness Numerals of Different Metals by Five Methods of Test

Metal	Shore sclero-scope	Hardness numeral				Bauer drill test	Ballan-tine test
		Brinell		Cone test			
		$\frac{P}{2\pi t R^1}$	$\frac{P}{t}$	90° cone	60° cone		
Carbon steel	86. 1	641	4550	....	....	....	3. 2
Silicon steel	33. 6	261	865	331	130	....	3. 0
Manganese steel	29. 5	179	641	368	124	....	3. 3
Cast iron No. 1	33. 3	149	538	191	68	....	3. 2
Cast iron No. 2	32. 9	172	590	231	79	2. 29	3. 3
Bessemer steel	26. 6	188	428	260	76	....	3. 3
Tool steel	37. 8	289	1230	....	....	....	3. 3
Cu.-sn. alloy 1	42. 4	110	460	130	50	. 73	3. 1
Cu.-sn. alloy 2	25. 5	105	323	149	54	1. 04	3. 2
Cu.-sn. alloy 3	22. 1	94	289	122	48	1. 24	3. 4
Copper 4	15	89	235	114	38	1. 88	3. 2

WASHINGTON, July 22, 1912.