* PRISM-HARDNESS :

A NEW METHOD OF TESTING HARDNESS IN MATERIALS; YIELDING A SCALE THAT IS EQUALLY APPLICABLE TO THE HARDEST AND SOFTEST METALS, AND EXPRESSES THE VALUES IN UNITS OF STRESS.

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Definition of Hardness.—The utility and popularity of the term “hardness” may be attributed, in part, to the flexibility of its meaning, which varies for different materials according to their applications in the Arts and Crafts. A hard bearing alloy and a hard carbon brush are hard in different senses, the one signifying resistance to flow under crushing stress, and the other resistance to abrasion. More commonly, as in diamond, tool-steel, and cast-iron, hardness relates to the processes of scratching, cutting or penetration.

Probably on account of this flexibility of meaning, the term has eluded scientific definition. Hardness seldom, if ever, signifies a single physical property of material; and it is improbable that any physical definition of the term—even if generally accepted—could fulfil all the varied functions of the current meanings. Any definition, to be serviceable in practice, must recognize the empirical nature of the quantity and admit the use of different scales to suit the different meanings of the term.

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[THE I.MECH.E.]

A definition which includes most of the current meanings and indicates the common characteristic of hardness tests, may be expressed as follows: The hardness of a material may be defined as a measure of its resistance to the complex and often indefinite stresses—complex in nature, whether compressive or shearing, and variable in magnitude and distribution—that are called into play in the course of *specific operations* such as scratching, abrasion, cutting, and penetration.

According to this definition, any given material may have many different hardness values, corresponding to the many operations that are met with in processes of manufacture or service, or in arbitrary methods of testing. A pair of materials may indicate different relative hardnesses on different scales, according to the natures of the operations adopted as the experimental bases of the corresponding tests. The value of any particular scale of hardness, as a guide in practice, depends on the degree of similarity between the process adopted in the test and the working conditions under which the material is used in manufacture or service. Although a limited degree of similarity may inspire some measure of confidence, nothing short of experience or research can demonstrate the validity of any particular hardness test as a guide for any particular class of service.

Research has shown that certain hardness scales are of service as indicating the approximate tensile yield-point and ultimate strength, as well as the crushing strength of the materials tested. To facilitate the tabulation of factors connecting these quantities it is desirable, although not essential, that hardness and strength should be measured in the same units, those of stress—tons per square inch or kilograms per square millimetre.

Although the use of consistent units facilitates the comparison of data from different sources and is, therefore, advantageous, it is still more important that the method of testing and the method of computation—adopted in the determination of empirical hardness values—shall be so related that the resulting values are, as far as possible, independent of the incidental conditions of the test, that is, independent of the dimensions of the test-piece and the tool, and

the magnitude of the load or blow employed in making the test. Failing such correlation, comparisons between data from different sources may prove misleading.

Principles Relating to a New Test of Hardness.—In endeavouring to devise an improved method of gauging hardness in metals, the Author drew up a summary of the fundamental principles involved. This is given below, with brief notes that indicate the bearing of the principles on the novel test described.

(1). Since surface hardness varies widely and affords little indication of that body-hardness which is generally more important, it is considered that the penetration method of testing—producing moderately deep indentations—is preferable to methods in which the surface is only lightly scratched or otherwise deformed. Indentation is a simple process and requires only a minimum of skill in its performance and measurement. On the other hand, indentation is possible only when the metal is endowed with some degree of ductility. Brittle metals, whether hard or soft, may crack before suffering measurable indentation.

(2). The test should be widely applicable, not only for structural metals of moderate hardness, but also for the hardest steels such as, at present, are difficult to test. Hardness being, indeed, more important in tool-steels than in structural metals, it is particularly desirable that the test should discriminate between superhard metals. Moreover, in order to compare the qualities of high-speed tool-steels under working conditions, the test should be such as can be carried out at high temperature.

The most obvious limitation to indentation tests, as at present performed, being the inability of the indenting tool—whether prism, ball or cone—to stand the loads required to produce deep indentations in materials as hard as or harder than itself, it occurred to the Author that a pair of test-pieces of the same material might be used to indent one another. Both pieces of the test sample would be deformed in the test, and either indentation would afford a measure of the common hardness. The test-pieces might be alike in form or different. A variety of forms might be used, for example, prisms, spheres, or cylinders.

(3). As superhard metals are commonly more or less brittle, the manner of indentation should be such that fairly large impressions are obtained without undue displacement of metal. And since brittleness is most apparent under tension, the form of test-piece and the method of loading should be such that the heavier stresses, occurring near the indentation, should act chiefly as compression combined with shear. As tensile stresses must occur in other parts of the test-piece, the indentations, in brittle materials, should not be too large in proportion to the dimensions of the test-piece. In the case of a test in which two pieces of the same material indent one another, it is probable that the displacement of metal is a minimum when the two pieces are alike in form.

(4). In order that the test may be directly comparable with the conditions of service of hard metals, and thereby afford a rational indication of relative hardness, the form of the test-piece and the method of loading should approximate to the conditions of action of cutting tools.

The indentation of a pair of cutting edges, by mutual pressure, suggests itself as comparable with such conditions. Fig. 1 indicates the method suggested. Two square prisms, placed crosswise with their edges in contact, are pressed together by a measured load. Alternatively, a pair of cylinders may be pressed together in the same manner, although, as will be explained, prismatic test-pieces offer considerable theoretical advantages.

(5). The test-pieces should be of simple form, with surfaces that can be finished, when necessary, by grinding. Although the simplicity of the Brinell and Shore test-pieces can hardly be attained in any test that requires a pair of samples, a fair degree of convenience may be obtained by using square prisms. In superhard materials, such prisms are readily finished by grinding.

To avoid the need for preparing special test-pieces, it is convenient to use the broken ends of Izod impact test-pieces—already machined as square prisms with 10 mm. side. In special circumstances, for example, in testing hard-drawn wire, it is convenient to use cylindrical test-pieces.

(6). To ensure that the hardness value indicated by a penetration

Jig to hold Test-pieces.

test does not vary with the load applied, the form of indentation must not vary, although its size increases, with the load. In terms of the hardness definition suggested above, the "specified operation" should be the same no matter what load is applied. As is well known, this condition is admirably fulfilled in the Ludvik cone test; but not in the Brinell ball test, in which latter, consequently, the hardness value varies with the load applied in making the test.

In the prism-test proposed, the form of indentation—shown diagrammatically in Fig. 2—is quite independent of the load. Provided that the indentation is not too large in proportion to the dimensions of the test-piece, the ratio between any pair of linear dimensions remains unchanged for different loads on a homogeneous material. This condition being fulfilled, we may apply the principle of similarity enunciated by Professor James Thomson* and extended by Professor Archibald Barr.† Similar bodies of homogeneous material are alike severely stressed and strained, whether within or beyond the elastic limit, by loads proportional to the squares of the linear dimensions, provided that these loads are applied in the same manner and similarly distributed. As a corollary to this theorem, it follows that the loads required to produce similar indentations in large bodies of homogeneous material are proportional to the squares of the linear dimensions of the indentations.

In the prism test described, consistent hardness values may, therefore, be deduced by dividing the applied loads by the squares of any characteristic linear dimension of the indentations produced, width or depth, according as the one or other may be preferred.

Width and depth both offer certain advantages in the case of the prism-indentation. Depths may be measured while the test-pieces are still under load; and a series of readings may be taken under successive loads. Widths can be measured, however, with greater inherent accuracy, and may be remeasured at any time after the test-pieces have been taken out of the testing-machine. As will be shown later, width offers the further advantage that the

* Journal, Inst. of Engineers and Shipbuilders in Scotland, 21st Dec. 1875.

† *Ibid.* 21st March 1899.

resulting hardness value is practically independent of the angle of the prism within broad limits.

In the tests described in the following pages, the Author measured the width of the indentation from corner to corner along the cutting edge (x , Fig. 2), and used this as the characteristic linear dimension of the indentation due to the measured load, P . "Prism hardness" is thence defined as the quotient

$$\text{"PH"} = \frac{P}{x^2},$$

which may be expressed in units of tons per square inch or kilograms per square millimetre. For example, a load of 4 tons, giving an indentation with a width $x = 0.2$ inch, would indicate a prism hardness of

$$\text{"PH"} = \frac{4 \text{ tons}}{(0.2)^2 \text{ in.}^2} = \frac{100 \text{ tons}}{\text{in.}^2} = \frac{157 \text{ kg.}}{\text{mm.}^2}.$$

It may be observed that the proposed test bears a superficial resemblance to that described in 1897 by Dr. W. C. Unwin *. In that well-known test, illustrated in Fig. 3, the rectangular test-piece is indented by steady pressure applied through a prismatic tool of hardened steel, ground to a 90° cutting edge. The indentation occurs only in the rectangular test-piece, the tool itself being unaffected. The load, P , and depth of indentation, d , follow an empirical relation $P = C.d^{1.2}$, where C is nearly constant for different loads and may be regarded as a measure of the hardness of the metal. As is well known, Unwin's test was the pioneer of all penetration tests using steady loads. The author's test differs in two fundamental respects, namely, the two pieces of metal are both taken from the sample under test, and are shaped so that the linear dimensions of the indentation are proportional to the square root of the load that is applied in making the test.

Apparatus Used in Prism-Hardness Test.—Like other penetration tests, the crossed-prism test may be carried out in any small compression testing-machine. The auxiliary apparatus required includes a microscope with eyepiece scale, or other means of

* Proceedings, Inst. C.E., Vol. 129, Part 3.

measuring the indentation, and a jig to hold the test-pieces in the correct relative position.

Fig. 4 and Fig. 5, Plate 12, show a jig comprising two blocks cut with 90° V-grooves to suit square test-pieces, and guided so that the cutting edges of the two prisms cross one another at right-angles. The guides are a pair of steel pins, screwed into the lower block and working through long brass bushes in the upper block. To minimize friction and ensure axial loading, the load is applied through a $\frac{5}{8}$ -inch steel ball that rests in spherical seatings in the upper holder and cap.

Fig. 6, Plate 12, shows the apparatus in place in a standard 3,000 kg. Brinell testing-machine. A Buckton 5-ton single-lever machine has, however, been used by the Author in nearly all the tests described in following pages. The load was then applied as follows:—The balance weight having been run out to about three-quarters of the intended load, the beam was “floated” by load applied through the test-pieces. The load was then increased gradually. After 30 seconds at the intended load, the balance weight was run back gently.

Four to six indentations were usually made with different loads on each pair of test-pieces, 3 inches in length. A hardness value was deduced from each indentation, and the several values were found in close agreement. In practice, a single indentation should suffice in nearly all cases.

The widths of indentation were measured, after the test-pieces had been removed from the jig, by means of a microscope fitted with micrometer traversing mechanism, as shown in Fig. 7, Plate 12. In practice, a simpler method would, doubtless, suffice. The microscope was fitted with a collimator eyepiece and 15 mm. objective, giving a 2-mm. field of view with fifty-six magnifications. The appearance of the field, showing the eye-piece graticule, is represented in Fig. 8, Plate 12. It is probable that the average variance of measurement was about 0.01 mm., equivalent to $\frac{1}{2}$ per cent on a 2-mm. indentation, corresponding to 1 per cent on the hardness value determined from an indentation of this comparatively small size.

The steel test-piece shown in Fig. 8 has a moderately sharp edge. Sharper edges are readily obtainable, but are not essential except in the hardest metals that take only small indentations under loads up to 5 tons. Soft and moderately hard steels, taking indentations from 3 to 7 mm. in width, were finished on rough emery, while harder steels were finished on finer grades. A tooled or rough ground finish should suffice in practice. As will be shown later, it is not essential that the angle of the prism should be exactly 90° . Provided that the faces of the test-piece are reasonably plane, consistent results are obtained although the prism-angle may vary appreciably.

Experiments on Different Metals.—Fig. 9 (page 900) summarizes the results of a number of prism-hardness tests on different metals. Each pair of prisms, cut from different samples, was tested under different loads as scaled along the base of the diagram. The ordinates give the corresponding hardness values, " PH " = $\frac{P}{x^2}$.

As both scales are plotted logarithmically, a series of diagonal lines serves to indicate the widths of indentation, x , observed in different experiments.

The diagram indicates that the hardness value of any particular sample is almost independent of the load used in making the test. Minor discrepancies, however, are apparent and fall into two categories:—(1) In the lower part of the diagram, relating to the softer metals, the hardness value tends to fall as the load increases. Thus, in soft copper, graph A, the value falls from 16.0 to 14.6 tons/in.² with loads increasing from 1 to 3 tons, a change of nearly 10 per cent, although the values at 10 and 20 cwts. are nearly identical. This variation is attributed to the use of comparatively small test-pieces ($\frac{1}{2}$ inch square), too small in proportion to the large indentations formed in soft metals by heavy loads. In this soft copper, the width of indentation under 3 tons was 0.453 inches = 90 per cent of the side of the prism. To ensure that the indentations under different loads are similar, and the corresponding hardness values consistent, it would appear desirable to limit the width of indentation to not more than half the side of the prism. (2) In several instances, small

FIG. 9.—Experiments on Different Metals.

A	COPPER, Anld.	I	0.18% C. Quenched.	Q	C. Chr. St. Quenched.
B	do. Hard drawn.	J	Mild Steel, Rolled.	R	do. Q & T.
C	NAVAL BRASS 60/39/1	K	Bessr. St. do.	S	1 1/2% C. Glass-hard.
D	DELTA IV	L	do. Overstrained.	T	Knife-edges
E	do II	M	Spring steel } soft.	U	Ni-Chr. St. Quenched
F	do I	N	Silver steel } soft.	V	do. Q & T.
G	Mild Steel	O	Engraving Steel	W	do. Tempered
H	0.18% C. Q & T.	P	C. Chr. steel, forged.		

but consistent variations of hardness may be attributed to non-homogeneous structure in the metal. Under light loads, the hardness value is determined, chiefly, by metal near the edge of the prism. Heavier loads strain deeper zones of underlying metal. The majority of the test-pieces having been cut from $\frac{1}{2}$ -inch or $\frac{5}{8}$ -inch square rolled bars, the corners may have been harder on account of over-rolling or softer owing to loss of carbon in steel or zinc in brass. In one or two instances, examined under the microscope, loss of carbon was clearly evident. Test-pieces cut from larger blocks showed no such variations.

It is considered that the experimental results support the application of Thomson's principle of similarity. No matter how small the load may be, indentation occurs in precisely the same manner—provided that the metal is homogeneous and the edges of the prism correspondingly sharp—and a correspondingly small quantity of metal is strained as severely as in tests under heavier loads. The character of the deformation does not depend upon the load applied.

The form of indentation varies, however, in different metals and with the heat treatment, and affords additional information regarding the nature and state of the metal. In the Brinell test likewise, the deformation of the metal surrounding the indentation varies in different metals; but the variations are less consistent because, in Brinell tests, the deformation varies also with the depth of the indentation. In certain metals, for example, soft copper and austenitic steel, the edges of the indentation are depressed below the level of surrounding metal which is raised above the original surface. This type of displacement spreads to a considerable distance, so that comparatively large volumes of metal are overstrained and, presumably, hardened. In other metals, for example, hard-drawn copper and martensitic steel, the displacement is more local, and the edges of the indentation are heaped up instead of being depressed. The contrast is illustrated in Figs. 10 and 11, Plate 13, which show the indentations of annealed and hard-drawn copper respectively. Although it appeared, at first sight, that the form of indentation was purely arbitrary, inspection showed that the

indentations of different metals could be classified in a well-defined sequence, as follows :—

Annealed copper	}	Capable of being further hardened by overstrain.
Austenitic steel		
Delta I and IV, Naval brass	}	Intermediate.
Delta II		
Ferritic steels		
Pearlitic steels		
Hard-drawn copper	}	Fully hardened.
Martensitic steels		

It was observed that the form of indentation was related, not to the actual hardness of the metal, but rather to its capacity for being further hardened by mechanical overstrain. Thus “Era” manganese steel and normalized 0·6 per cent carbon steel, although nearly alike in hardness ($\frac{P}{x^2} = \frac{70 \text{ tons}}{\text{in.}^2}$), showed markedly different indentations.

It is probable that the form of the indentation affords a simple qualitative means of anticipating certain characteristic properties of the metal, particularly its capacity for being further hardened by mechanical treatment and, as a consequence, the form of the stress-strain diagram for ductile strain. Pending further investigation, it may be anticipated, also, that the form of the indentation will afford a serviceable indication of the factors that may be applied to estimate, from the measured prism-hardness, the probable tensile yield-point, ultimate strength, etc.

Comparative Tests on Copper (Fig. 12).—In these experiments, samples $\frac{1}{2}$ inch square were cut from a single $\frac{5}{8}$ -inch square bar of hard-drawn copper. Two series were tested, hard-drawn as received (D) and fully annealed (A). In each series, comparative Brinell- and Prism-hardness tests were made with different loads. The results obtained by the prism method are as follows (plotted in graphs “PH”) :—

Load.	Tons.	$\frac{1}{2}$	1	2	3	4
“PH” (D)	$\frac{\text{tons}}{\text{in.}^2}$	31·3	31·8	52·4	(30·8)	(30·4)
“PH” (A)	$\frac{\text{tons}}{\text{in.}^2}$	16·0	16·1	(15·3)	(14·6)	—

FIG. 12.—Comparative Tests on Copper.

PH PRISM-HARDNESS, P/x^2 ;

BH BRINELL BALL-HARDNESS, $P \div \text{AREA OF INDENTATION}$;

CH MODIFIED BALL-HARDNESS, $P \div \frac{\pi}{4} d^2$, 10 m.m. BALL.

(BH & CH, as well as PH, expressed in TONS per Sq. INCH)

D HARD-DRAWN COPPER;

A SAME COPPER, ANNEALED.

Cutting out the results obtained with the heavier loads (on account of the unduly large size of the indentations) the probable hardness values are 31.5 and 16.0 tons per sq. inch, indicating that the drawn metal is 96 per cent harder than the annealed.

Brinell tests, using a standard 10 mm. ball, gave the following results :—

Load.	Tons.	$\frac{1}{2}$	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4
"BH" (D)	$\frac{\text{tons}}{\text{in.}^2}$	55.3	55.3	—	53.0	50.6	48.9	44.7*	42.0*
"BH" (A)	$\frac{\text{tons}}{\text{in.}^2}$	26.5	28.3	29.6	29.2	29.0	28.2*	—	—
Ratio $\frac{(D)}{(A)}$		2.09	1.95	—	1.81	1.74	1.73	—	—

The Brinell values vary with the load applied, particularly in the case of the hard-drawn sample; and the ratio between the values for the two samples varies even more widely. Although the values marked by asterisks may be left out of consideration, in view of the perceptible bulging of the $\frac{5}{8}$ -inch bar under the heavier loads, the drawn metal may be anything from 110 to 75 per cent harder than the annealed.

In the above Table, the Brinell hardness values - expressed in $\frac{\text{tons}}{\text{in.}^2}$ instead of the more customary $\frac{\text{kg.}}{\text{mm.}^2}$ - have been computed by the standard method, dividing the load by the contact area of the spherical indentation, $A = \frac{\pi}{2} D (D - \sqrt{D^2 - d^2})$. Alternatively, a modified Brinell value may be computed by dividing the load by the projected area of the indentation, $A^1 = \frac{\pi}{4} d^2$. On the latter basis, the values are somewhat greater, as follow :—

Load.	Tons.	$\frac{1}{2}$	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4
CH" (D)	$\frac{\text{tons}}{\text{in.}^2}$	56.3	57.0	—	57.3	56.6	55.6	53.2*	52.2*
CH" (A)	$\frac{\text{tons}}{\text{in.}^2}$	27.6	30.6	33.1	34.1	35.5	36.1*	—	—
Ratio $\frac{(D)}{(A)}$		2.04	1.86	—	1.68	1.60	1.54	—	—

The ratio between the values for the two samples varies at least

as widely as before; but the variation arises, chiefly, from the figure for the annealed sample. It appears that neither method of calculating the Brinell hardness gives consistent results in both samples.

The Brinell graphs, BH (D) and BH (A), plotted in Fig. 12, indicate maxima of 55.5 and 29.6 tons per sq. inch, respectively 1.75 and 1.85 times as great as the values obtained by the prism method. The ratio between the Brinell maxima, 1.88, may be regarded, probably, as the figure that is most comparable with the 1.96 hardness ratio indicated by the prism tests. Brinell tests with the larger and smaller standard loads of 3,000 and 500 kg. indicate hardness ratios of 2.09 and 1.73 respectively.

Effect of Change in Prism Angle.—Prior to an investigation on the point, it was anticipated that the results of prism-hardness tests would vary widely with the angle of the prism; but experiment shows that minor changes in the prism angle hardly affect the numerical value of the ratio $\frac{P}{x^2}$ where x is the width of the indentation, measured from corner to corner along the cutting edge.

Experiments were carried out on samples of the hard-drawn copper used in the foregoing tests. Pairs of test-pieces were cut to different angles from 60° to 150°, and tested with loads of 1 and 2 tons. The hardness values, $\frac{P}{x^2}$, obtained in this series are as follow :—

Prism-angle	60	86	90	94	120	150
$\frac{P}{x^2}$ tons in. ²	32.6	31.5	31.4	30.5	30.4	30.3

The variation is too slight, in comparison with unavoidable experimental variance, to deduce any empirical relation; but the total variation between 60° and 150° is only 7 per cent—less than $\frac{1}{10}$ per cent per degree. Had the depth of the indentation been used, instead of the width, as the characteristic linear dimension x , the results would have varied widely because the depth of indentation is much greater with the sharper angles. Figs. 13 and 14, Plate 13, illustrate the contrast between the indentations obtained with 60° and 120°.

Further experiments were carried out on a pair of prisms having unequal angles, namely, 86° and 94° :—

Load P	For the 86° prism.		For the 94° prism.		Mean.
Tons.	x in.	$\frac{P}{x^2}$	x in.	$\frac{P}{x^2}$	$\frac{P}{x^2}$
1	0.186	28.9	0.176	32.3	30.6
2	0.267	28.1	0.248	32.6	30.3

The mean of the two means, 30.45 $\frac{\text{tons}}{\text{in.}^2}$, is approximately 3 per cent less than the mean of the three values obtained with the 86°, 90° and 94° pairs. The discrepancy is attributed, in part, to the slightly lower hardness (30.5) of the 94° sample. In other tests, in which the two prisms have differed slightly in hardness, the results have likewise approximated to the true value for the softer of the two samples.

It is inferred that variations in the prism-angle, within the limits of ordinary workmanship, have little influence on the results of the prism-test. The prism-angle may be varied even widely without producing any important change in the hardness value. The values may, therefore, be termed “prism-hardness”—in distinction from ball- or cone-hardnesses—without reference to the prism-angle.

In order to avoid splintering brittle materials—whether hard or soft—it may be advisable, occasionally, to use prism-angles greater than 90°. The right-angle, however, is doubtless more convenient as a general standard, more particularly as the broken ends of Izod impact test-pieces, machined to 90°, are commonly at hand.

Tests on Copper Alloys.—Series of tests were carried out on naval-brass (60-39-1) and Delta metals, I, II, and IV, supplied in square or round bars from which $\frac{1}{2}$ -inch square prisms were cut. The samples were not annealed or otherwise heat-treated. The results of prism-hardness tests with different loads are as follows :—

Load.	Tons.	1	2	3	4	5
	$\frac{\text{tons}}{\text{in.}^2}$					
Naval-brass.		36.5	35.8	35.3	34.8	33.5
Delta I	„	60.3	61.4	59.6	57.7	58.0
„ II	„	60.9	59.8	57.9	56.3	—
„ IV	„	43.6	44.2	43.4	42.4	41.8

The naval-brass, which was of good commercial quality (ultimate tensile 26·8 tons/in.², 25½ per cent elongation on 6¼ diameters, yield point about 11 tons/in.²) gave peculiarly variable results in Brinell tests, as follows :—

Load, lb. (10 mm. ball)	200	400	600	1,000	2,000	3,000	4,000	5,000	6,000.
Brinell, $\frac{\text{kg.}}{\text{mm.}^2}$	63	64	78	79	89	87	90·5	92	93.

Taking the probable value for the standard 3,000 kg. load as 93 kg./mm.² = 59·2 tons/in.², and the probable prism-hardness as 36·5 tons/in.², the ratio between the hardness values is 1·62.

Except in the case of Delta II, which proved somewhat brittle, no difficulty was experienced in testing any of these alloys by the prism method. In Delta II, the corners of the indentation showed a tendency to split away under heavy loads, and it was not, therefore, practicable to apply the full load of 5 tons on the ½-inch prism. No difficulty of this sort was experienced in the Brinell test, which gave comparatively consistent figures in the case of Delta II, namely :—

Load in kg., 10 mm. ball	500	1,000	1,500	2,000	2,500	3,000
Brinell, $\frac{\text{kg.}}{\text{mm.}^2}$	140	145	150	152	154	153

Comparing the Brinell value for 3,000 kg., namely, $\frac{153 \text{ kg.}}{\text{mm.}^2} = \frac{97·3 \text{ tons}}{\text{in.}^2}$ with the prism value 60·5, the ratio between the two is found to be 1·61.

Tests on Pearlitic Steels.—Four series of tests were made on a forged steel containing about 0·18 per cent carbon. The different series correspond to different heat-treatments, namely, (1) material tested as forged; (2) after quenching in water from 890° C.; (3) quenched in water from 890° C. and tempered for 30 minutes at 300° C.; (4) treated as 3 but finally quenched in oil from 800° C. The results obtained are as follows :—

Load.	Tons.	½	1	2	3	4	5
	$\frac{\text{tons}}{\text{in.}^2}$						
PH (1)		49·2	49·7	50·0	50·6	49·2	48·8
PH (2)	„	—	80·5	80·5	84·0	70·0	70·0
PH (3)	„	—	63·2	60·7	61·3	63·9	63·4
PH (4)	„	—	58·8	58·0	56·9	58·1	58·0

The irregular figures obtained in the second (quenched) set are attributed to the condition of the steel.

The above results may be compared with Brinell tests carried out with the standard load of 3,000 kg. on a 10 mm. ball.

Sample Number	(1)	(2)	(3)	(4)
PH (as above)	49.6	70 80	62.5	58.0
Brinell $\frac{\text{kg.}}{\text{mm.}^2}$	135	200	170	155
BH $\frac{\text{tons}}{\text{in.}^2}$	85.8	127	108	98.5
Ratio $\frac{\text{(BH)}}{\text{(PH)}}$	1.73	1.8-1.5	1.73	1.70

When the two hardness values are expressed in the same units, tons/in.², the Brinell value is 70-75 per cent greater than the prism-hardness value.

Another sample of mild-steel, giving a tensile of 31 $\frac{\text{tons}}{\text{in.}^2}$ ultimate, gave similar prism-hardness values, namely :—

Load.	Tons.	1	2	3	4	5
PH	$\frac{\text{tons}}{\text{in.}^2}$	54.8	53.3	52.9	52.0	51.2

The gradual fall of hardness with increasing load, in this instance, is attributed to irregular structure caused by rolling at moderate temperature. The steel, which had been rolled to a $\frac{1}{2}$ -inch square bar, showed the masked yield-point which, in a tensile test, characterizes cold working. It is probable that the corners of the bar were harder than the underlying metal.

Four samples of a harder steel, containing 0.43 per cent C., were also tested after different heat-treatments (1) as forged ; (2) forged and quenched in water from 850° C. ; (3) treated as 2 and then tempered for 30 minutes at 300° C. ; (4) treated as 3 and finally quenched in oil from 750° C. The results may be summarized as follows :—

Sample	(1)	(2)	(3)	(4)
PH $\frac{\text{tons}}{\text{in.}^2}$	70.2	189	102	81.2
BH „	117.5	380	216	127
Ratio $\frac{\text{(BH)}}{\text{(PH)}}$	1.67	2.0	2.1	1.56

A bar of Bessemer steel was tested before and after being strained in direct tension, with $8\frac{1}{2}$ per cent elongation, giving two sets of values as follows :—

Load.	Tons.	1		3	4	5
PH (before)	$\frac{\text{tons}}{\text{in.}^2}$	75·7	75·8	75·3	75·4	75·7
PH (after)	„	85·7	83·7	84·2	84·3	84·1

The increase of hardness, due to straining, is approximately 12 per cent. In a tensile test, the steel showed a yield-point of 40·5 tons/in.² and extended $8\frac{1}{2}$ per cent when the load was increased by 19 per cent. The ultimate strength was 53·8 tons/in.², and the elongation at fracture 15·2 per cent with 50·5 per cent reduction of area.

Samples of “Spring-steel” and “Silver-steel” gave results nearly alike as follows :—

Load.	Tons.	1	2	3	4	5
PH (spring)	$\frac{\text{tons}}{\text{in.}^2}$	75·2	78·5	78·6	79·7	79·5
PH (silver)	„	78·3	79·8	80·4	81·2	—

In these samples, the gradual increase of hardness with load is attributed to difference of composition. Transverse sections, under the microscope, showed that the carbon percentage was distinctly lower at the corners than in the middle of the bars.

Two high-carbon tool steels, containing $1\frac{1}{4}$ and $1\frac{1}{2}$ per cent carbon, were tested in $\frac{1}{2}$ -inch square bars, as received, without heat-treatment. The results were nearly alike, namely :—

Load.	Tons.	1	2	3	4	5
PH ($1\frac{1}{4}$ per cent C.)	$\frac{\text{tons}}{\text{in.}^2}$	102·0	107·0	107·2	102·0	103·1
PH ($1\frac{1}{2}$ per cent C.)	„	103·0	105·0	100·2	100·7	100·2

Brinell tests with 3,000 kg. on 10 mm. ball indicated 286 and 277 kg./mm.² respectively. The ratios between the Brinell and prism values, expressed in the same units are, therefore, 1·70 and 1·79 respectively. Under 2,000 kg., the Brinell values were alike, namely, 258, corresponding to ratios of 1·61 and 1·58. In carbon steels, the value of the ratio appears to run from 1·60 to 1·80 in different samples.

The foregoing experiments indicate that the prism-hardness of pearlitic carbon-steel increases from about 50 with 0·18 per cent carbon to 100 tons/in.² with 0·9 per cent, and thereafter remains approximately constant; but the value varies, naturally, with the heat treatment as well as the carbon percentage.

Test on Austenitic Manganese Steel.—A sample of “Era” manganese steel, tested by the prism and Brinell methods, gave the following figures :—

Load.	Tons.	1	2	3	4	5
PH	tons in. ²	71·8	71·4	70·2	68·8	68·7
BH		107	119	120	122	125

Although the prism hardness of “Era” is thus no greater than that of a normalized 0·7 per cent carbon steel, the form of the indentation is markedly different, resembling that of annealed copper. Only in this respect does the hardness test give any evidence of the remarkable quality that the metal possesses, namely, abnormal hardening with overstrain. The gradual fall in prism-hardness with increase of load is attributed to the small size of the test-piece and to the comparatively wide-spread displacement that occurs in this metal. Taking the probable hardness values, PH and BH, as 71·8 and 120 tons/in.², the ratio between the two is 1·67—approximately the same as in Pearlitic steel.

Tests on Martensitic Steels.—Prior to a number of tests on high-carbon and alloyed steels of great hardness, it had been anticipated that Martensitic steels might splinter in the prism test, without forming regular indentations. Experiment showed, however, that even the hardest carbon-steels can be indented by the prism method, with 90° angle; and that splintering occurs only in brittle samples when the load exceeds a value that is amply sufficient to yield a measurable indentation. The form of the indentation, in Martensitic steel, resembles that obtained in hard-drawn copper, but is even more local.

Three series of tests were made on a high-carbon alloy steel, as used in the bearing balls employed in making Brinell tests. The three samples had received different heat-treatments, namely,

(1) normalized, as delivered ; (2) heated to 800° C. for 15 minutes and quenched in water ; (3) treated as (2) and tempered at 390° F. for 10 minutes. The results obtained in prism tests were as follows :—

Load.	Tons, in. ²	1	2	3	4	5	Mean.
PH (1)		76·2	74·5	75·4	74·9	72·5	74·7
PH (2)	„	314	310	323	316	326	318
PH (3)	„	265	276	276	259	266	268

It is evident that tempering, even at the moderate temperature of 200° C., has resulted in 16 per cent loss of hardness. It is interesting to note, also, that the maximum hardness of this alloy steel is some 18 per cent less than that observed in subsequent tests on simple carbon steels.

Similar results were obtained in tests on other alloyed steels, hardened and tempered at different temperatures, giving prism-hardness values from 325 to 240 tons/in.²

Four knife-edges, in the form of $\frac{1}{2}$ -inch square bars, afford an example of the hardness attainable in carbon steel. The four bars had been hardened on different dates, in works practice, and were untempered. Two had been rejected, namely, sample C for brittleness, and sample D for water cracks. Prism tests gave the following hardness values :—

Load.	Prism Hardness.		tons in. ²			
Tons.	Sample	A	B	C	D	
$\frac{1}{4}$		—	—	359	383	
$\frac{1}{2}$		282	403	357	358	
$\frac{3}{4}$		288	—	354	—	
1		298	392	359	376	
$1\frac{1}{4}$		293	—	345	—	
$1\frac{1}{2}$		289	382	*	393	
$1\frac{3}{4}$		—	—	—	387	
2		294	380	—	*	
3		287	373			
4		283	378			
5		237	387			
Means		286	385	355	380	

Samples B, C and D appear to be fully hardened, while A is

decidedly softer. The hardness values do not vary with load more widely than may be attributed to experimental variance or slight changes of structure, and may be regarded as independent of the load applied in making the test. Although A and B gave consistent values and regular indentations with all loads up to the maximum of 5 tons, samples C and D invariably splintered when the load reached a certain limit which, in each sample, was fairly definite as marked by asterisk in the Table. Splintering occurred under lower loads applied jerkily.

This evidence of brittleness, although it limits the load that can be applied in making the test, is probably a serviceable feature. Thus the foregoing tests show that sample B is not merely as hard as or harder than D but much tougher. As compared with B—which is the hardest metal yet tested by the Author—sample C is lacking alike in hardness and toughness.

In the foregoing samples, splintering occurred locally, chips flying from the edges of the indentation, which then collapsed. In other cases, test-pieces cracked transversely when the load reached a limiting value. This occurred in a sample of $1\frac{1}{2}$ per cent carbon steel, hardened by quenching in cold water. Under loads of 2 and 3 tons, this brittle specimen gave consistent prism-hardness values of 350 tons/in.²; but at $3\frac{1}{2}$ tons the test-pieces snapped. The limiting load does not appear to depend on the sharpness of the angle, but rather, on the transverse dimensions of the test-piece.

Up to the present, no tests have been made at temperatures other than 60–75° F., but apparatus is in hand for testing samples up to red-heat. It is anticipated that prism-hardness tests on high-speed steels will yield figures indicating a gradual, or eventually more rapid fall in hardness with increasing temperature; and that comparisons between different steels should prove serviceable as a guide to the permissible working temperatures. Although hardness tests on such steels, at air temperature, are of little practical value, it may be of interest to note that one sample, tested cold under 5 tons applied near the working edge, showed a prism-hardness of 277 tons/in.².

It is considered that the crossed-prism hardness test should be

of service in many fields of research. The consistent results and convenience of the method are evident; and, in the Author's experience, the test has proved sensitive to slight differences of hardness, even in the hardest metals. As one and the same scale—a scale of stress—is equally applicable for the hardest and softest metals, the prism test should prove serviceable as a reference standard.

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The Paper is illustrated by Plates 12 and 13 and 6 Figs. in the letterpress.

Fig. 5. *Jig with Crossed Prisms in place.*

Fig. 6. *3,000 Kg. Brinell Testing-Machine with Jig for Crossed-prism test.*

Fig. 7. *Measuring Microscope used for taking widths of indentations; with Mild-steel Prism in place.*

*Shows other Prisms, viz.,
Hard-drawn Copper,
Austenitic Steel,
Martensitic Steel.*

Fig. 8. *Corner of Indentation as viewed with high magnification through the Measuring Microscope, with graticule.*

Fig. 10.
*Widespread
Indentation
in Annealed Copper.*
×2½.

Fig. 11.
*Localized
Indentation
in Hard-drawn
Copper.*
×2½.

Fig. 13.
*Side view
of Indentation
in 60° special
prism.
Hard-drawn
Copper.*

Fig. 14.
*Plan View
of Shallow
Indentation
in 120° special
prism.
Hard-drawn
Copper.*