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A SENSITIVE PYRAMIDAL-DIAMOND TOOL FOR INDENTATION MEASUREMENTS

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ABSTRACT

A sensitive diamond indenting tool was developed which gives indentations of accurately measurable length in the most resistant steels with loads of less than 1 kg. It was found that the use of these light loads permits extension of indentation tests to small specimens and to tests of brittle materials, such as glasses, which shatter under the heavy loads required by present indenters.

The indenter is pyramidal in form, giving a diamond-shaped (rhomb) indentation of which the diagonals have an approximate ratio of 7 to 1 instead of 1 to 1 for the square-based pyramid. Such indenters were duplicated to the required accuracy and showed no discernible wear with use.

Elastic recovery of indentations with this indenter takes place in a transverse rather than a longitudinal direction, and, consequently, from the measured length of the long diagonal and the constants of the indenter, unrecovered dimensions of an indentation are obtained. Results of tests are expressed as indentation numbers which relate the applied load in kilograms to the unrecovered projected area in square millimeters.

Recovered projected areas also, may be determined with an added measurement of the short diagonal. Since knowledge of both recovered and unrecovered dimensions may be obtained, the indenter offers possibilities for study of the fundamentals involved in indentation testing that are not afforded by ball, cone, and square-based pyramidal indenters, which, because of their symmetrical form, yield recovered dimensions only.

The performance of seven indenters of different angular formation was investigated to determine their relative sensitivity and adaptability for use in different materials and to determine also the effect of load and of different dimensional bases of computation on indentation number. Consideration of the results led to the selection of an indenter which gives excellent performance in many materials. Comparison is made of indentation numbers given by this indenter and corresponding Brinell and Vickers numbers for the same specimens.

CONTENTS

I. INTRODUCTION

1. INDENTATION TESTING

The merits of indentation tests which account for their universal application are concisely stated in a recent National Bureau of Standards paper:[1] "The chief value * * * of an indentation test lies in its simplicity, in the fact that it measures a combination of properties that has proved significant in the choice of metals, and that it can be used to check the uniformity of a given product by making and measuring a few indentations in that product." The result of a test is usually expressed as an indentation number, commonly called a "hardness" number, in which the load applied to the indenting tool is related to the lateral area, projected area, depth, or volume of the indentation after the indenter has been removed. Results thus obtained are interpreted as a measure of "hardness," which is defined by Osmond[2] as "the resistance to permanent deformation." However, because of the elastic properties of materials, the dimensions of an indentation may change appreciably upon removal of the loaded indenter. Consequently, it appears somewhat more logical to associate the applied load with dimensions under load, or "unrecovered" dimensions, rather than with those of the final indentation. This is the view favored by O'Neil,[3] since "in this way both the elastic and plastic deformation are incorporated in the test."

[1] Serge N. Petrenko, Walter Ramberg, and Bruce Wilson, *Determination of the Brinell number of metals,* J. Research NBS **17**, 59 (1936) RP903.

[2] M. F. Osmond. Comm. des Méthodes d'Essai des Matériaux de Construction (1895), **3A**, 279.

[3] Hugh O'Neil, The Hardness of Metals and Its Measurement (The Sherwood Press, Cleveland, Ohio, 1934). The development of indentation testing, a description of the various methods, and an extensive bibliography are given.

2. FORMS OF INDENTERS

(a) INDENTERS IN COMMON USE

In the development of indentation methods, many shapes of indenting tools have received attention, and of these the ball, cone, and square-based pyramidal forms, which because of their symmetry yield dimensions of the final indentations only, have come into general use. These indenters have proved applicable to specimens of sufficient size and have the inherent characteristics to withstand the heavy loads required to produce indentations of the magnitude necessary for accurate measurements, but they are of little value in testing brittle materials like glass and small specimens, including thin metal films.

(b) DEVELOPMENT OF THE DIAMOND-BASED PYRAMID INDENTER

One shape of indenting tool which has not been used extensively is the regular pyramid with diamond-shaped (rhomb) base. Earliest use of this sensitive indenter appears to have been by Major W. Wade [4] in 1850–51 for testing the hardness of cast iron. Later, at his suggestion, its use was extended to measurement of the pressure of gas in the bore of a gun by an indentation method devised by Captain T. J. Rodman.[5] In each case the indenter was made of steel. Martel [6] used similar steel tools to determine the hardness of metals by a dynamic indentation method. Restricted dissemination of the excellent results obtained by Wade and Rodman may account for the failure of other investigators to develop further the elongated pyramidal indenter. The indenting diamond, ground to the form of a square-based pyramid by Smith and Sandland,[7] which is, of course, a special case of the elongated pyramidal indenter, seems to be the only later application. Results obtained with diamond indenting tools of the elongated pyramidal shape [8] indicate that this indenter deserves greater recognition in that (1) it makes possible accurate measurements of unrecovered indentations, (2) it extends the application of indentation tests to glass and other brittle materials as well as to specimens of small size, and (3) it permits a better understanding and possible evaluation of elastic recovery and other physical properties which are involved in indentation measurements. Later developments indicate that this indenter may find application in testing fields other than that of hardness. In addition to its use by Rodman for the measurement of gas pressures within guns, its use by H. C. Dickinson and S. A. McKee of the Lubrication and Liquid Fuels Section of the National Bureau of Standards for measuring wear of airplane-engine cylinder walls has increased the measuring accuracy appreciably. These applications may in turn suggest to other workers added uses for these indenting tools.

3. PURPOSE OF THIS INVESTIGATION

The excellent performance of the diamond-based pyramid indenting tool from the standpoint of sensitivity, well-defined indentations, and reproducibility of results, in testing glass and crystals of the Mohs

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[4] Reports of experiments on metals for cannon by officers of the U. S. Ordnance Dept., 1856 (Henry Carey Baird, Philadelphia, Pa.).

[5] Reports of experiments on metal for cannon and cannon powder. U. S. Ordnance Dept., 1861. (Chas. H. Crosby, Boston, Mass.).

[6] Martel. Comm. des Méthodes d'Essai des Matériaux de Construction **3A**, 261 (1895).

[7] Smith and Sandland, Proc. Inst. Mech. Eng. **1**, 623 (1922). Smith and Sandland, J. Iron and Steel Inst. **61**, 285 (1925).

[8] Hardness testing device. U. S. Patent 2091995 issued to Frederick Knoop and assigned by him to the U. S. Government.

scale [9] and dental plastics and enamels,[10] appeared to warrant a more extensive consideration of this indenter. The authors believed that its general characteristics could be best developed by the use of indenters with different pyramidal angles in specimens which present the fewest testing complications and which could also be tested with the usual forms of indenters, thus giving the added advantage of direct comparison with other indentation scales. The results of such tests are presented with the hope that they will prove of value to those who require an indenter which is more sensitive than the ball, cone, or square-based pyramid, and one which also yields reliable quantitative indentation measurements with applied loads of less than 1 kg.

II. DIAMOND-BASED INDENTING TOOL

1. DESCRIPTION

The indenting tool consists of a diamond crystal of 0.25 to 1.5 carats rigidly mounted in a metal holder for cutting and use. Figure 1 shows, schematically, one of the shapes used in the present work, together

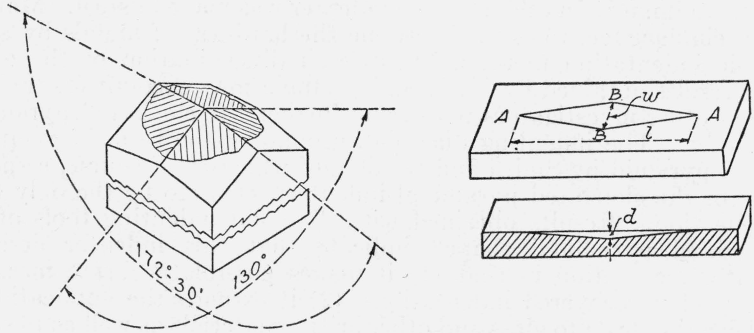

FIGURE 1.—*The diamond indenting tool.*

with its resulting indentation. The sensitivity of this indenter results from its elongated shape, which, for this tool, gives an indentation of length, l, that is about 7 times the width, w, and 30 times the depth, d. From consideration of displacement, it is evident that a specimen under load will be greatly strained at BB and relatively unstrained beyond A, A. This is substantiated by examination of indentations in transparent materials in polarized light and, also, by the appearances of indentations in brittle materials under excessive loads, which show decreasing rupture of the specimens from a maximum at B to none at A. These considerations indicate that the major part of the elastic recovery of an indentation upon removal of the indenter will take place crosswise rather than lengthwise of the indentation. Further, although only the modulus of cubic compressibility of the diamond has been measured, its high value (5.5×10^{12} dynes/cm^2) makes it certain that the relative deformation of a diamond indenter will be small in comparison with the deformation of the indented material. Consequently, from the measurement of a single dimension, l, and

[9] C. G. Peters and Frederick Knoop, *Measurements of relative hardness of glasses*, Glass Ind. **17**, 153 (1936).

[10] George C. Paffenberger, Irl C. Schoonover, and Wilmer Souder, *Dental silicate cements: Physical and chemical properties and a specification*, J. Am. Dental Assn. and the Dental Cosmos **25**, 32–87 (Jan. 1938).

from the indenter constants in terms of l, a close approximation to the unrecovered width, lateral or contact area, projected area, penetration, and volume becomes known; and with an added measurement of the width, w, of the final indentation, the recovered projected area may likewise be determined.

2. PRODUCTION, DUPLICATION, AND WEAR

Previous to this investigation, apparatus had been devised and the necessary technique developed by one of the authors for cutting diamonds to the angular shapes required for indenting tools. These cut diamonds have plane faces which intersect in edges that appear straight and free from the most minute nicks when viewed under a magnification of 75. The angles of these diamonds can be readily measured to the required accuracy, and indenters can be duplicated with an exactness sufficient to give the same results on a given material within the experimental errors. Cut diamonds seem to show little wear when used for indenting purposes; in fact, no wear was discernible in the indenters used in the present work after 2 years' service. The manufacturers of Vickers testing machines find that diamond indenters in continual service require relapping at intervals varying from 6 months to 2 years.

III. PRELIMINARY CONSIDERATIONS FOR THE INDENTATION TESTS

1. VARIOUS INDENTERS USED

In a preliminary endeavor to select a suitable indenting tool for microindentation testing, indenters 1, 2, 3, and 4 were cut with the angles given in table 1, and, of these, indenter 4 was selected for general use. Quarter-carat diamonds were used for these tools, and although they were sufficiently large for microindentation testing, larger diamonds were necessary to meet the requirements of the extended investigation. Indenter 5 is a larger diamond cut to duplicate and to extend the measuring range of 4, and a comparison of the measured angles of the two indenters shows the exactness with which indenter 4 has been duplicated. Indenters 6 and 7 were designed to give added investigational information, and indenter 8 approximates the shape selected on the basis of this study as probably the most suitable for general indentation testing. Constants for these indenters and also for the Vickers indenter of Smith and Sandland are given in the table.

TABLE 1.—*Constants of the indenters*

A_P=projected area.
A_L=lateral or contact area.
p=penetration.
V=volume.
l=length of longitudinal diagonal.
w=length of transverse diagonal.

Indenter	Included angle between edges				Constants, C, relating dimensions with length, l				Ratios		
	Transverse		Longitudinal		$C_P \times 10^2$ $(A_P=C_Pl^2)$	$C_L \times 10^2$ $(A_L=C_Ll^2)$	$C_p \times 10^2$ $(p=C_pl)$	$C_V \times 10^4$ $(V=C_Vl^3)$	$\frac{\text{Length } (l)}{\text{Width } (w)}$	$\frac{\text{Length } (l)}{\text{Penetration } (p)}$	$\frac{\text{Lat. area } (A_L)}{\text{Proj. area } (A_P)}$
	deg	*min*	*deg*	*min*							
1	118	36	175	20	3.43	3.99	2.04	2.33	14.57	49.1	1.164
2	134	15	174	53	5.29	5.75	2.23	3.94	9.44	44.8	1.086
3	126	36	171	42	7.21	8.09	3.63	8.72	6.93	27.6	1.121
4	126	12	173	52	5.28	5.93	2.68	4.72	9.47	37.3	1.123
5	126	6	173	52	5.27	5.92	2.68	4.70	9.49	37.3	1.123
6	136	0	170	44	10.03	10.85	4.05	13.55	4.99	24.7	1.082
7	100	36	170	0	5.27	6.86	4.38	7.68	9.49	22.9	1.303
8	129	40	172	32	6.94	7.69	3.26	7.55	7.20	30.6	1.107
Vickers	148	[a] 7	148	[a] 7	50.00	53.93	14.29	238.2	1.00	7.0	1.079

[a] The angles between opposite faces of Vickers indenters are 136°.

2. INDENTING AND MEASURING APPARATUS

In making indentation tests, apparatus is required (a) to apply a known load to an indenter at a constant rate of speed and for a definite contact period and (b) to measure the resulting indentations. The devices for making and measuring indentations are frequently incorporated in a single unit to facilitate and expedite the testing. Since in the present case the limiting requirements of these indenters were undetermined, a simple exploratory device for applying loads was constructed for microindentation testing, and advantage was taken of existing commercial testers for applying large loads.

(a) MECHANISMS FOR APPLYING LOADS

The instrument for applying loads up to 0.5 kg to an indenter is shown in figure 2. A calibrated lever arm carries a sliding weight, *W*. The arm is provided with pivot points near one end and carries indenter, *I*, at its other extremity. A sliding and elevating specimen holder is shown at *H*. The indenter is raised to its correct position above the specimen by a cam-and-lever arrangement which lifts piston rod, *R*, of dashpot, *P*. The rate of uniform descent of *I* is controlled by a valve in *P*. The whole assembly is mounted on a base provided with levels and levelling screws.

Loads of 10 to 45 kg were applied by means of commercial deadweight machines made available through the courtesy of the Engineering Mechanics Section of the National Bureau of Standards; and to span the range 0.5 to 10 kg, the arm of the small instrument was heavily weighted to give fixed loads of 1, 2, and 4 kg.

(b) APPARATUS FOR MEASURING INDENTATIONS

Lengths and widths of indentations were measured by means of a micrometer microscope. Its sensitivity was such that one to six divisions (depending upon the microscope objective) on the screw head

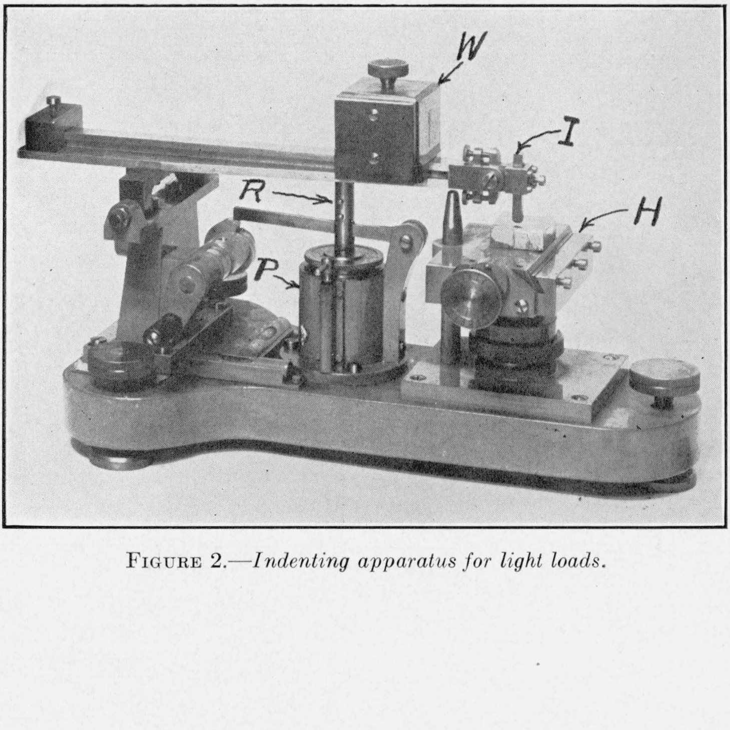

FIGURE 2.—*Indenting apparatus for light loads.*

were equivalent to 1 μ. The micrometer screw was calibrated with a steel line standard ruled by light waves. A green filter within the vertical illuminator eliminated eyestrain.

3. SPECIMENS

(a) MATERIALS AND SPECIMENS SELECTED

The following materials and specimens were originally selected for test:

Material	Specimen
Steel	Rockwell test blocks *C 25*, *C 47*, *C 65–67*. NBS, gage blocks 1 and 2.
Brass	Rockwell test block *B 7–9*.
Copper	Rolled.

Specimens of medium flint glass, cast and electrolytic copper, cast and rolled platinum, cast and rolled gold,[11] cast aluminum, cast tin, and stainless steel were also used during the investigation. Since interest lay in the performance of the indenters rather than in a study of materials, the chemical composition of the specimens was not determined.

(b) SIZE

All specimens were sufficiently large so that differences in indentations could not be attributed to the size of the specimens.

(c) PREPARATION

Surfaces were lapped and polished plane and free from scratches to increase the accuracy of measurement and to avoid differences in indentation determinations which might result from surface irregularities with the light loads and small resulting penetrations in some of the tests.

4. NOTES ON INDENTING PROCEDURE

(a) SETTING THE INDENTER

The direction of motion of the indenter was made normal to the surface of the specimen by means of suitable adjustments. The symmetry of an indentation is a critical indication of the proper setting when regular indenters and plane specimens are used. Some lack of symmetry may be in evidence without affecting appreciably the indentation numbers.

(b) RATE OF DESCENT OF THE INDENTER

The rate of descent of the indenter was varied from 36 mm/min to 1 mm/min for each material. Indentation results were the same for rates not exceeding 18 mm/min (which for the mechanism used was equivalent to a descent of 3 mm in 10 sec); therefore, this 18 mm/min rate was adopted for all tests.

(c) CONTACT PERIOD

The time that indenter and specimen remained in contact was varied from 10 sec to 4 min. This type of indenter appears to reach static equilibrium quite rapidly, and no change in indentation number occurred in the more resistant materials after 20 sec; the decrease for

[11] These specimens were actually rolled from gold castings. "Rolled gold" has a somewhat different meaning in the jewelry trade.

rolled gold was about 1 percent when the contact time was increased from 20 sec to 120 sec, and was less than 4 percent for cast copper when the time was increased from 20 sec to 4 min. A contact period of 20 sec was selected as standard for testing all materials.

5. COMPUTATION OF INDENTATION NUMBERS

Indentation results are expressed in the form of numbers which relate the unrecovered projected areas to the loads applied to the indenters. Or

$$I=\frac{L}{A_P}=\frac{L}{l^2C_P},$$

in which:

I=indentation number.
L=load (in kilograms) applied to the indenter.
A_P=unrecovered projected area of the indentation (in square millimeters).
l=measured length of the long diagonal of the indentation (in millimeters).
C_P=constant relating l to the projected area.

The indentation number corresponding to a measured length, l, for a given load and a given indenter may be read from a chart.

Reasons for selecting the unrecovered projected area for computational purposes and consideration of some of the factors which may affect the indentation numbers are developed in succeeding pages.

IV. EXPERIMENTAL OBSERVATIONS

1. TYPES OF INDENTATIONS

In general, the types of indentations for various materials may be classified according to the contour of the surface adjacent to the ends of the transverse diagonal; namely, type *A*, those having a definite ridge; type *B*, those having no visible disturbance of the original surface level; and type *C*, those in which the surface level appears depressed.

Type *A* is shown in figure 3 (*A*). Height, h, of the ridge decreases from a maximum at the ends of the transverse diagonal to zero as it approaches the ends of the longitudinal diagonal. Lateral boundaries of the elevated surfaces are shown for rolled copper and for *C 25* steel in figure 4. Optical tests show that the greatest height of the ridge is at the immediate edge of an indentation.

Although no disturbance of the surface surrounding a *B*-type indentation is visible by microscopic inspection, interferometric examination shows a slight uniform elevation extending over a considerable area as in figure 3 (*B*). A slight sinking of the surface at the immediate edge of the indentation is indicated in some materials. The height of the raised surface is small compared to the penetration of the diamond for this class of indentation. The general outline of the disturbed surface of a specimen of tin can be seen in the upper photograph of figure 5. The fine scratches at 45° to the long diagonal show the original lapped surface. After the indentation had been made, the surface was again lightly lapped at right angles to the indentation. The fine lap marks in this direction show the outline of the raised area. This (shown more definitely at the left of the indentation) corresponds approximately with the outline of the strain patterns of indentations in glass when viewed in polarized light, and, also, with the shape which fractures tend to take when a brittle specimen is shattered by a heavily loaded indenter.

In type-*C* indentation the surface for a considerable distance beyond the ends of the short diagonal is depressed as in figure 3 (*C*). This type is recognized in the microscope by the inability of an observer to obtain a sharp focus for width measurements and may be illustrated by the lower photograph, figure 5, for cast gold. Here again the diagonal scratches represent the original surface. These scratches remain in the sunken-in material adjacent to the indentation, whereas the raised surrounding area shows the lap marks at right angles to the indentation.

It seems well to call attention to the marked decrease in width relative to length of indentations in elastic materials. With one exception, all indentations in figure 6 were made with the same indenter, and by comparing the indentations in glass and hardened steel with those in the less elastic stainless steel, narrowing of the indentation is readily seen.

The appearance of indentations obtained with several types of indenters by the application of light loads is shown in figure 7. The faint circular mark at the extreme right of the lower photograph (glass) results from the application of 2 kg to a Brale indenter. All indentations in steel were made by indenters under the same load (1 kg); consequently, the photograph illustrates the relative sensitivity of the various indenting tools.

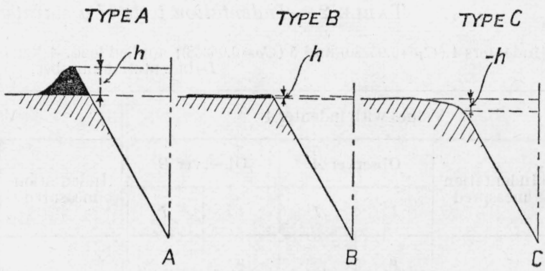

FIGURE 3.—*Types of indentations.*

Indentations with ball, cone, and square-based pyramidal indenters are usually classified as "ridging" and "sinking-in" types, and the type of indentation is commonly associated with the capacity of a specimen to be work-hardened. With the present indenter the demarcation of types is not distinct for metals, and cold-working of such materials as cast gold, platinum, and copper changes the indentations from a nonridging or sinking-in type to a ridged indentation.

2. INDENTATION TESTS OF A STAINLESS STEEL WITH INDENTERS 4 AND 5 UNDER THE SAME LOAD

Measurements of the included angles of indenters 4 and 5 showed them to be alike in a longitudinal direction and to differ by 6 min in a transverse direction. Tests were made to determine the differences in indentation numbers that would result from the substitution of one indenting tool for the other, to show the uniformity in length of indentations produced by a given indenter, and to show, also, the spread in length measurements of an indentation by the same and by different observers. The tests were made on an inclusion-free 14-percent-chromium stainless-steel specimen which was carefully heat-treated and polished to a plane optical surface. Five indentations were made with each indenter under a 4-kg load, and four measurements of the length of an indentation were made by each of two observers.

The results of the test are presented in table 2. Observer *A* obtained an indentation number with indenter 4 that was 0.3 percent greater than that obtained with indenter 5, whereas observer *B* obtained a number with indenter 4 which differed from that obtained with indenter 5 by less than 0.05 percent. The values by *A* were 0.4 percent greater than those by *B* using indenter 4, and 0.2 percent greater using indenter 5. The spread of readings by these two observers is of approximately the same magnitude as that of a larger group on another steel specimen. The individual indentations with a given indenter appear to be uniform in size within the limits of measurement. The data indicate that the difference, if any, in indentation numbers with indenters 4 and 5 is small and is masked by the uncertainties of measurement by the same or by different observers.

TABLE 2.—*Indentation tests of a stainless-steel specimen*

[Indenters 4 (C_P=0.05280) and 5 (C_P=0.05268); applied load, 4 kg; l=measured length of an indentation I=indentation number]

Values with indenter 4					Values with indenter 5				
Indentation measured	Observer *A*		Observer *B*		Indentation measured	Observer *A*		Observer *B*	
	l	I	l	I		l	I	l	I
	μ		μ			μ		μ	
First	391.6	494.0	391.6	494.0	First	393.7	489.9	393.4	490.6
	391.6	494.0	392.0	493.0		393.7	489.9	393.0	491.6
	391.6	494.0	391.6	494.0		394.1	488.9	393.0	491.6
	391.6	494.0	391.6	494.0		393.7	489.9	393.4	490.6
Mean		494.0		493.8	Mean		489.7		491.1
Second	391.6	494.0	393.0	490.5	Second	391.6	495.1	392.0	494.1
	391.6	494.0	392.3	492.3		391.3	495.9	392.3	493.4
	391.6	494.0	392.7	491.3		392.0	494.1	392.3	493.4
	392.0	493.0	392.3	492.3		392.3	493.4	392.0	494.1
Mean		493.8		491.6	Mean		494.6		493.8
Third	391.6	494.0	393.0	490.5	Third	392.7	492.4	392.3	493.4
	392.0	493.0	392.3	492.3		393.0	491.6	393.0	491.6
	391.3	494.8	392.7	491.3		393.7	489.9	393.4	490.6
	392.7	491.3	393.0	490.5		393.0	491.6	393.0	491.6
Mean		493.3		491.2	Mean		491.4		491.8
Fourth	391.3	494.8	393.0	490.5	Fourth	391.6	495.1	393.4	490.6
	392.3	492.3	392.3	492.3		392.3	493.4	393.0	491.6
	391.3	494.8	392.3	492.3		391.6	495.1	392.7	492.4
	392.3	492.3	393.0	490.5		392.3	493.4	393.0	491.6
Mean		493.6		491.4	Mean		494.3		491.6
Fifth	391.3	494.8	393.0	490.5	Fifth	392.3	493.4	393.4	490.6
	391.6	494.0	393.0	490.5		392.0	494.1	393.4	490.6
	391.3	494.8	392.7	491.3		393.0	491.6	393.4	490.6
	390.9	495.8	393.0	490.5		392.3	493.4	393.0	491.6
Mean		494.9		490.7	Mean		493.1		490.9
Average of means		493.9		491.7	Average of means		492.6		491.8

Observer	*I(indenter 4)*	*I(indenter 5)*	*Difference (percent)*
A	493.9	492.6	0.3
B	491.7	491.8	.0
Mean	492.8	492.2	0.1

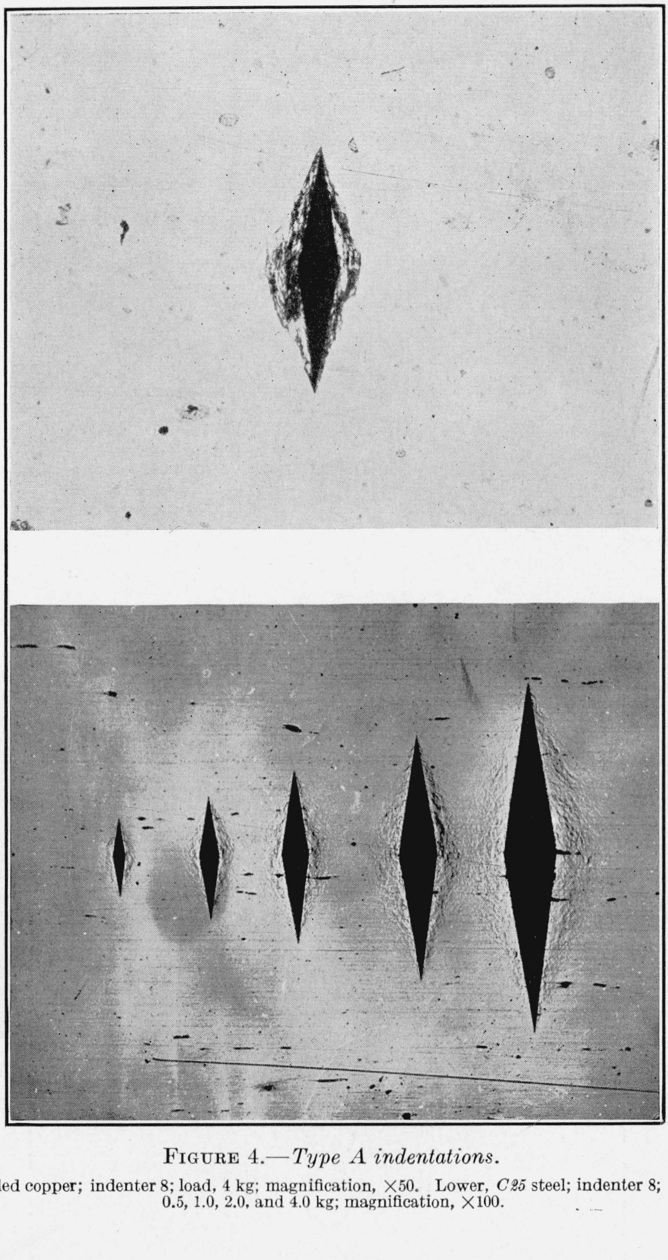

FIGURE 4.—*Type A indentations.*

Upper, rolled copper; indenter 8; load, 4 kg; magnification, ×50. Lower, *C25* steel; indenter 8; loads—0.2, 0.5, 1.0, 2.0, and 4.0 kg; magnification, ×100.

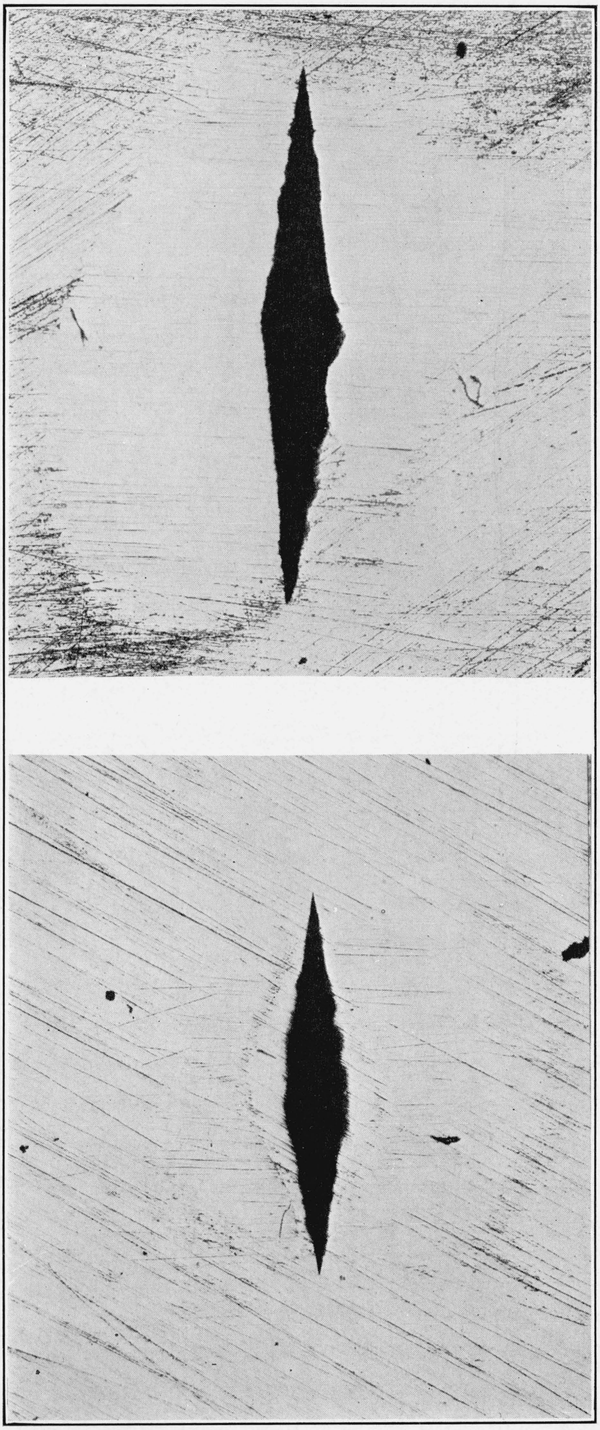

FIGURE 5.—*Type B and type C indentations.*

Upper, tin; type *B*, magnification, ×35. Lower, cast gold; type *C*, magnification, ×35.

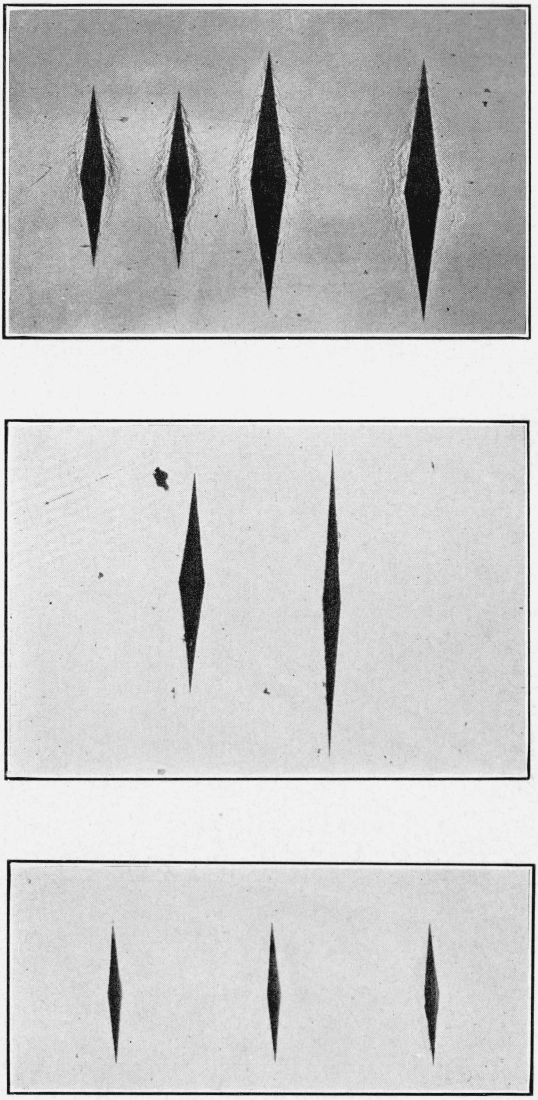

FIGURE 6.—*Indentations in specimens having different elasticities.*

Upper, stainless steel; indenter 8; loads, 2 and 4 kg; magnification, ×100. Central, *C65–67* steel; left, indenter 8; right, indenter **1**; load, 4 kg; magnification ×110. (Although the indentation on the right shows indenter 1 to be extremely sensitive, its use in elastic materials is to be avoided. Because of the transverse recovery, the end sof indentations are not sufficiently abrupt to be fully resolved. Greater measuring accuracy may be obtained with a less sensitive indenter having a smaller l/w ratio.) Lower, medium flint glass; indenter 8; load, 1 kg; magnification, ×100.

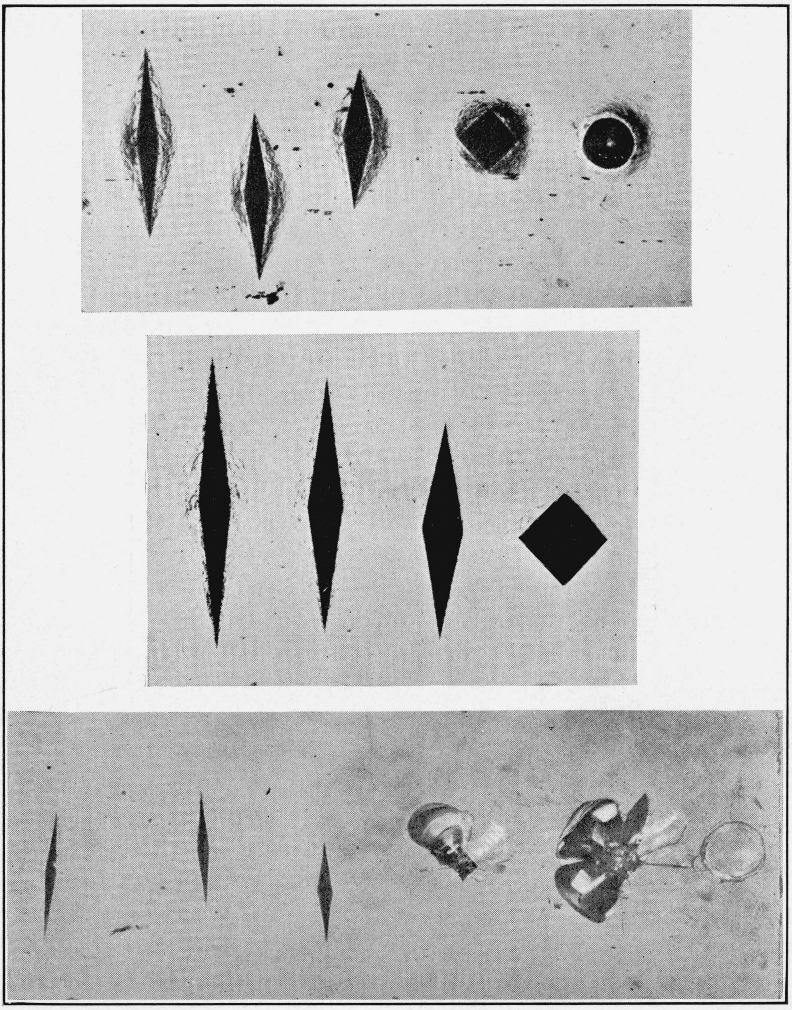

FIGURE 7.—*Indentations with different indenters.*

Upper, *C25* steel; indenters 4, 8, 6, Vickers, and Brale; load, 1 kg; magnification, ×50. Central, stainless steel; indenters 4, 8, 6, and Vickers; load, 1 kg; magnification, ×100. Lower, medium flint glass; indenters 4, 8, 6 (1 kg), Vickers (0.5 and 1.0 kg), and Brale (2 kg); magnification, ×90.

3. EFFECT OF LOAD UPON INDENTATION NUMBER

Indentation numbers were determined for specimens of steel, copper, and glass with loads of 0.1 to 4.0 kg, using indenter 4 with an 18 mm/min rate of descent and a 20-sec contact period. Five indentations were made for each load and the mean value was used for computing. All indentations were sharply defined at the ends of the long diagonals. Length readings by the same or by different observers usually agreed to 1 μ, and adjacent marks gave the same uniformity; but indentations scattered over the surface indicated a lack of homogeneity of 2 or 3 percent for some specimens. To extend the range of the tests, loads up to 45 kg were applied to specimens by indenter 5, which was inserted in Rockwell and Vickers testing machines.

The results of the tests, table 3, appear to give either a decrease in indentation number with load or a surface hardness effect for light loads in several specimens. However, more uniform results were obtained from lengths measured with a microscope having greater

TABLE 3.—*Variation of Indentation Number with Applied Load*

[Indenter 4, 0.1 to 4.0 kg: indenter 5, 15.0 to 45.0 kg]

Applied load	Lengths of indentations and indentation numbers													
	Rolled copper		Steel *C 25*		Glass, med. flint		Steel *C 47*		Steel gage 1		Steel gage 2		Steel *C 65–67*	
	l	*I*	*l*	*I*	*l*	*I*	*l*	*I*	*l*	*I*	*l*	*I*	*l*	*I*
kg	μ		μ		μ		μ		μ		μ		μ	
0.1	124.5	122	82.5	278	69.2	395	62.5	485	51.7	708	47.6	835	46.6	872
0.2	176.0	122	117.4	275	100.2	377	88.1	488	74.3	686	66.9	846	67.4	834
0.3	214	125	143.7	275	123.6	372	108.0	487	90.8	689	82.5	834	82.6	833
0.4	248	124	163.9	282	142.4	373	124.8	486	104.6	693	95.5	831	95.8	825
0.5	276	125	184.6	278	160.4	368	139.4	487	117.9	681	107.6	818	107.7	816
1.03	393	126	263	282	231	365	198.8	494	171.5	663	155.8	804	155.1	811
2.0	550	126	367	282	-------	-----	276	497	240	659	218	797	216	812
4.0	783	124	524	276	-------	-----	392	493	342	649	311	782	307	804
15.0	1,513	125	1,005	282	-------	-----	759	494	669	635	606	775	597	800
30.0	-------	-----	1,425	281	-------	-----	1,077	491	944	639	857	775	846	795
45.0	-------	-----	-------	-----	-------	-----	1,321	490	-------	-----	1,054	768	1,037	795

magnification, thus indicating that ends of the indentations may not have been fully resolved even with the higher power. This effect was noticeable only in materials, such as hard steel and glass, in which elastic recovery (and hence, transverse contraction) of indentations was large. Inability to resolve the final micron ending of a 100 μ-indentation would cause an apparent increase in indentation number of 4 percent, and this error would be increased for shorter indentations. To minimize the end effect, it is desirable to use loads (for example: 0.1 kg for rolled copper and 0.5 kg for *C 65–67*) which will give indentations of at least 100 μ, length. Minute nicks in an early indenter gave a similar false effect of surface hardness. The curves, figure 8, which are based upon measured lengths greater than 100 μ, show that indentation numbers do not vary appreciably with load. The small differences shown by some specimens may be attributed either to a variation with load or to a slight surface hardness.

4. INDENTATION TESTS WITH ELONGATED PYRAMIDAL INDENTERS HAVING DIFFERENT INCLUDED ANGLES

Indentation tests were made on the selected specimens with the different indenting tools to determine the variation in indentation number for indenters of different angular shape, and, at the same time, to give additional observational data on the characteristics of the tools in various materials. Tests were made with loads of 1 and 4 kg using indenters 1, 2, 3, and 4, and with loads of 4, 15, 30, and 45 kg, using indenters 5, 6, 7, and 8 whenever the size of the diamond and the resistance of the specimen permitted the use of large loads. (Results with indenter 5 will be recorded as extensions of measurements with indenter 4, since the two indenters yield the

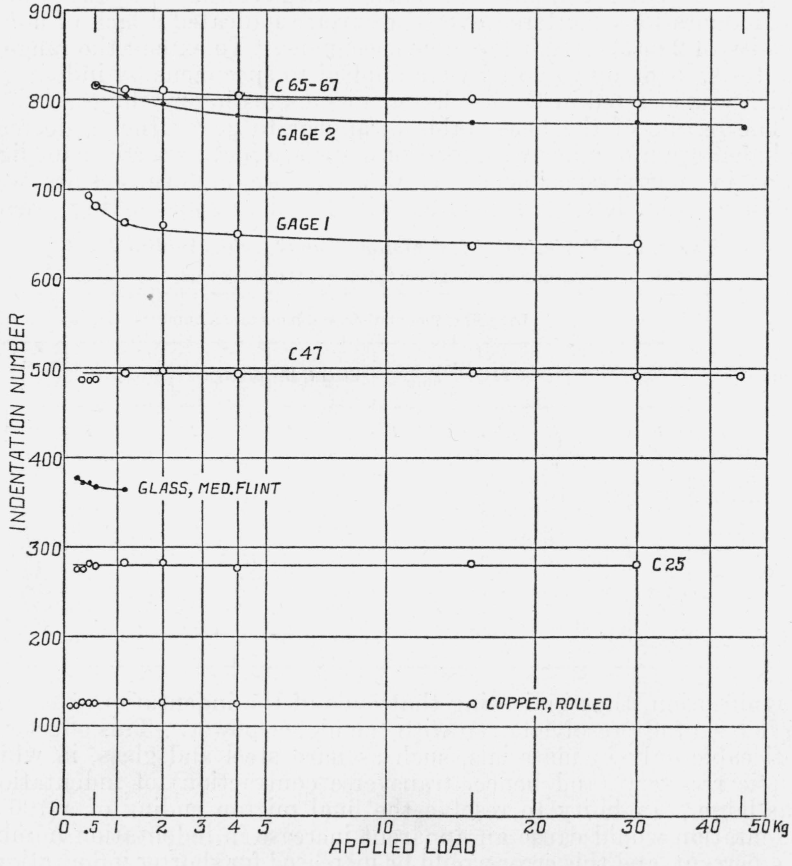

FIGURE 8.—*Effect of load on indentation number.*

Indenter 4, to 4 kg; indenter 5, from 15 to 45 kg.

same indentation numbers.) Indentation numbers with a given-indenter and specimen were found to change but slightly with loads which exceeded 4 kg, yet, for consistency, comparison of results with different indenters was based upon tests with a 4-kg load whenever possible.

There seems to be no unanimity of opinion as to which dimension of an indentation should be used for computing indentation numbers. Present tests were computed on each of several bases which are available with elongated pyramidal indenters: namely, volume of material displaced by the indenter; penetration of the indenter; lateral area (contact area of indenter and specimen); unrecovered projected area;

and recovered projected area. The results of the tests were compiled in the form of curves that show the change in indentation number with angular shape of the indenter, using different bases of computation—the purpose being that data so presented might aid in establishing a dimensional basis for calculating indentation numbers.

(a) INDENTATION NUMBERS WITH DIFFERENT INDENTERS, USING PENETRATION AND UNRECOVERED VOLUME

Various formulas were used for computing indentation numbers on the basis of penetration of the indenter and of volume of material displaced. Relations $I=kg/p^2$(in mm) and $I=\sqrt{kg}/p$ for penetration computations and $I=kg/V$ (in mm^3)$^{2/3}$ and $I=(kg)^{3/2}/V$ for volume computations gave indentation numbers which remain constant for different loads with a given indenter. Figures 9 and 10 give the difference in percentage of numbers obtained with a given indenter from those with indenter 4, which was selected as a reference standard. The abscissas have no meaning except to show the spacing of the various specimens in the indentation scale of indenter 4. Actual indentation numbers for a given indenter may be obtained by increasing the value for 4 by the percentage difference given by the ordinates.

The differences in indentation numbers (fig. 9) result from the rela-

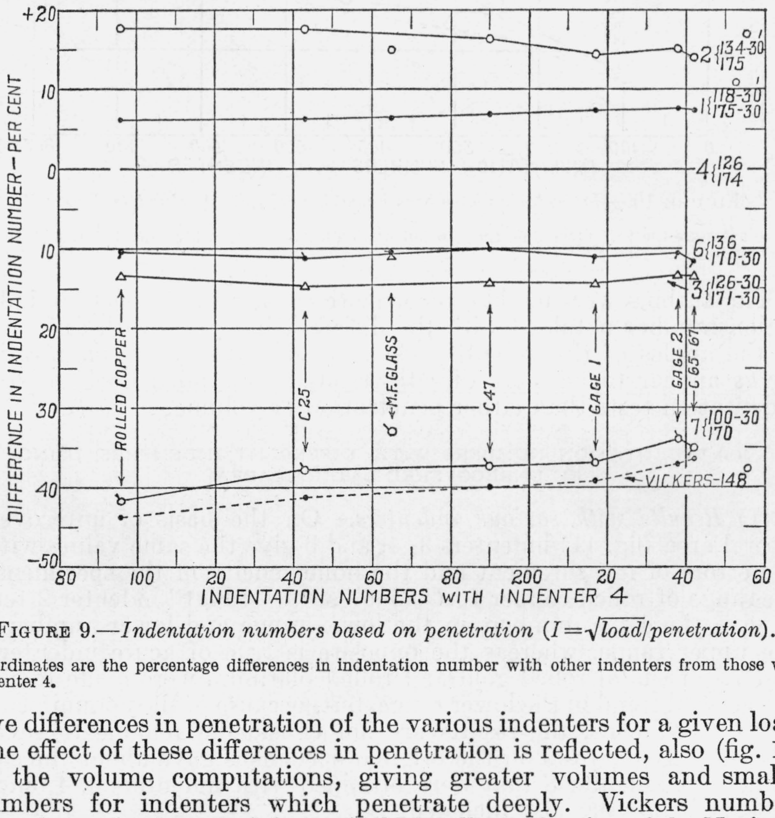

FIGURE 9.—*Indentation numbers based on penetration* ($I=\sqrt{load}/penetration$).

Ordinates are the percentage differences in indentation number with other indenters from those with indenter 4.

tive differences in penetration of the various indenters for a given load. The effect of these differences in penetration is reflected, also (fig. 10) in the volume computations, giving greater volumes and smaller numbers for indenters which penetrate deeply. Vickers numbers were determined by the Mechanical Metallurgy Section of the National

Bureau of Standards, and, from these, penetrations and volumes were computed. Since there was evidence of strain in the specimens at the ends of the diagonals of the Vickers indentations, and, hence, possible elastic recovery, the Vickers numbers may not be strictly unrecovered values and, therefore, not truly comparable with those computed on the basis of unrecovered dimensions for elongated pyramidal indenters.

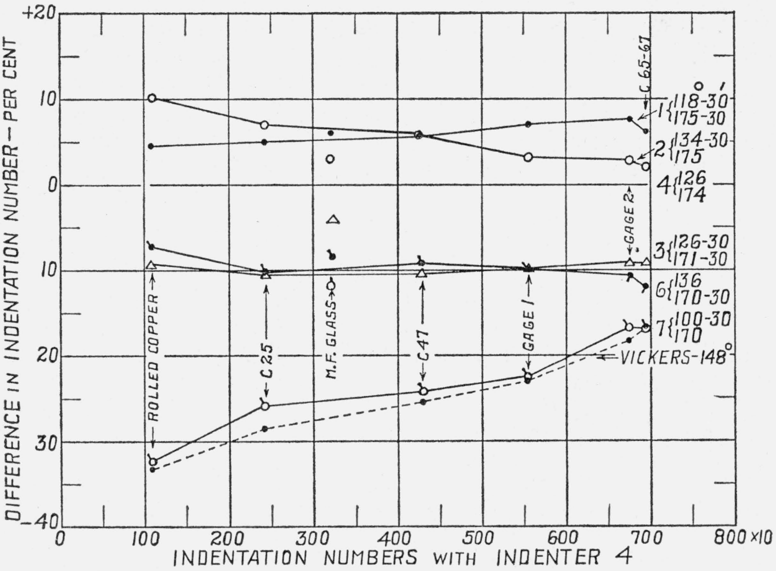

FIGURE 10.—*Indentation numbers based on volume* (I=*load*/(*volume*)$^{2/3}$).

Ordinates are the percentage differences in indentation number with other indenters from those with indenter 4.

The authors were unable to correlate the large differences in indentation number obtained with the different indenters with differences in the angles of the indenters using these methods of computation. *Areas* appear to be more directly related to applied loads in static indentation tests than either penetration or volume.

(b) INDENTATION NUMBERS WITH DIFFERENT INDENTERS, USING UNRECOVERED LATERAL AREA

(1) *Results with various indenters.*—On the basis of unrecovered lateral area (fig. 11) indenters 3, 4, and 6 give the same values within the errors of measurement and the homogeneity of the specimens in the range of rolled copper to *C 65–67* steel. "Flat" indenter 2 tends to give the same numbers in the lower range and lower numbers in the upper range, whereas the opposite is true of acute indenters 1 and 7. Tests of rolled gold and rolled platinum were made to show the general trend in the lower range, but, because of the nonuniformity of the specimens, the results are not considered reliable to several percent. Later tests on the original specimens gave about the same values for indenter 8 that were obtained with indenters 3, 4, and 6. Vickers values are also included.

Indentation numbers were also determined for specimens of cast tin, aluminum, gold, platinum, and soft brass which yielded nonridging and sinking-in indentations. These specimens gave evidence of surface hardness, probably caused by cold-working during the preparation of the specimens, that confused the results. Better comparative determinations must await the preparation of more uniform specimens. The mean results with these cast materials gave the arrangement for the various indenters which is shown by the dotted lines, but because of the inhomogeneity of the materials no great credence should be given to the values for these cast materials.

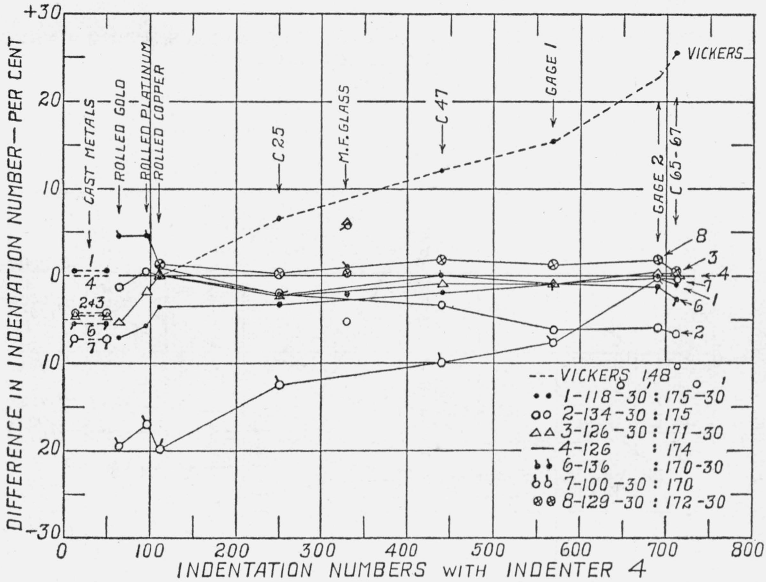

FIGURE 11.—*Indentation numbers based on unrecovered lateral area.*

Ordinates are the percentage differences in indentation number with other indenters from those with indenter 4.

(2) *Effect of ridge upon indentation numbers.*—The rolled gold, platinum, copper, and steel specimens gave ridged indentations, and it was considered probable that indentation numbers might be greatly affected by the support the indenter received from the ridged material, which, for the rolled copper specimen, gave an added supporting area of 30 percent for indenter 7. Examination of the ridge showed it to be of ruptured material which was easily removed by light polishing. The following tests were made to determine the amount of support which indenter 8 received from the ridge in a specimen of rolled sheet copper. Preliminary measurements showed that the copper was of uniform hardness; that no measurable change in indentation lengths occurred with contacts exceeding 20 sec; and that reinsertion of the indenter in the welted indentation gave no increase in length. Lengths and widths of the indentations were measured and the maximum height of the ridge was determined interferometrically. From these, the area of contact of indenter and elevated material was determined to be 18 percent of the unrecovered

lateral area as computed from the length measurements. Next, another indentation was made; the elevated material was removed by light polishing in place; and the load was applied to the ridgeless indentation. Repeated trials showed that the increase in length after removal of the ridge did not exceed 0.5 percent. Thus, while the elevated material added 18 percent to the lateral area, it actually supported less than 1 percent of the load. The same disproportionate effect of excess area and supporting force was found for steel gage 1. Since the required correction was less than the differences in uniformity of most of the specimens, no corrections for ridge were applied to the computed lateral areas.

(c) INDENTATION NUMBERS WITH DIFFERENT INDENTERS, USING UNRECOVERED PROJECTED AREA

Figure 12 presents the results of the same experimental data computed on the basis of unrecovered projected area. Indentation num-

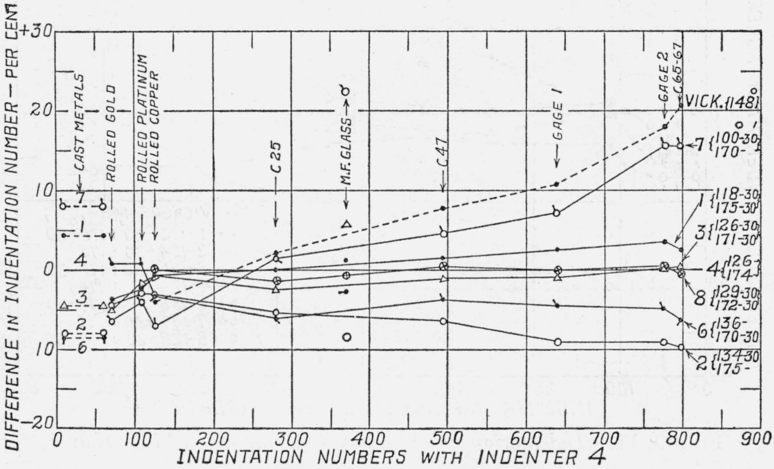

FIGURE 12.—*Indentation numbers based on unrecovered projected area.*

Ordinates are the percentage differences in indentation number with other indenters from those with indenter 4.

bers with the different indenters tend to approach the same values for inelastic materials, giving type-*A* indentations, and to depart for the more elastic materials, differences in elasticity being indicated by the transverse recovery of indentations. This departure seems to be definitely related to the indenter shape, with acute indenters giving progressively greater numbers for the more elastic materials. The transverse angle appears to be the effective angle to be related to difference in indentation number, although its action may be modified by the longitudinal angle, as shown by indenters 2 and 6. Values for the Vickers indenter are included, although, in view of the increasingly greater elastic recovery for specimens in the upper range, it is quite possible that the curve for the square-based pyramid might fall below that of indenter 7 if actual unrecovered areas were used. An orderly arrangement appears even in the questionable results (broken lines) with cast materials. The resistance to indentation of these cast materials increases greatly with mechanical working, and to what extent the difference in strain-hardening of the present specimens by the various indenters contributes to the orderly arrangement shown in figure 12 has not been determined.

The results appear to indicate that some factor or combination of factors based upon angular shape might be applied which would bring the results of all indenters into agreement.

(d) INDENTATION NUMBERS WITH DIFFERENT INDENTERS, USING RECOVERED PROJECTED AREA

Indentation numbers based on recovered projected areas were determined from the measured lengths and the measured widths of the indentations which were used in previous computations. The percentage differences in indentation numbers with the various indenters are plotted (fig. 13) relative to indenter 4. No comparative data are

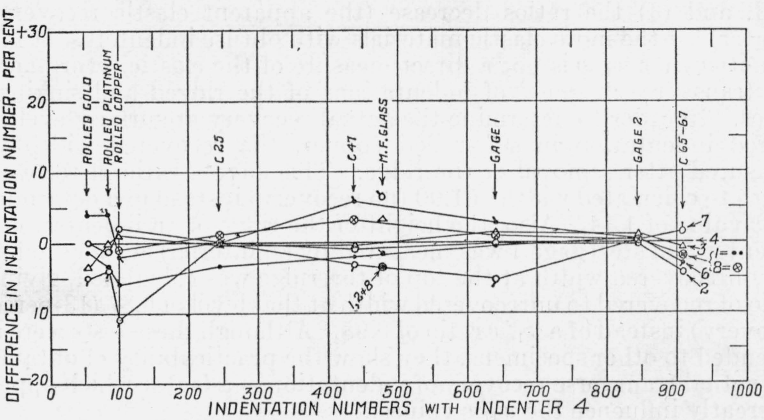

FIGURE 13.—*Indentation numbers based on recovered projected area.*

Ordinates are the percentage differences in indentation number with other indenters from those with indenter 4.

available for the Vickers indenter. The curves indicate a better agreement of indentation numbers for the different indenters in the more elastic specimens on this basis than on the basis of unrecovered projected area. The errors of measurement are greater, however, because of the small magnitude of the widths and because of the greater uncertainty in measuring diagonals which end in disrupted surfaces. For rolled copper, on which exceedingly high ridges were raised by indenters 1 and 7, the width of the indentations could not be measured with great exactness. Because of doubt as to the comparable accuracy of the indentation measurements for medium flint glass, which were obtained with an applied load of only 1.0 kg, with those of other specimens, values for flint glass were plotted but not included in the curves (figs. 11 and 12). It is of interest to note, however (fig. 13), the closer agreement of numbers with the several indenters for the glass on the basis of recovered projected area than on the basis of unrecovered projected area, and to note, also, the relative position of the glass in this indentation scale. Because of its great elastic return, the glass appears "harder" than *C 47* steel on the basis of recovered dimensions, whereas the latter was the more resistant on the basis of unrecovered dimensions.

(e) RELATION BETWEEN (c) AND (d): w_1/w RATIO

The authors would like to call the attention of those interested in theoretical considerations involved in indentation measurements to certain data collected during the investigation: namely, the ratio of the measured width, w_1, of the recovered indentation to the width, w, of the unrecovered indentation as calculated from the measured length and the indenter constants. The w_1/w ratios for the different materials and indenters are arranged in table 4 in the order of the acuteness of indenters, indenter 7 being the most acute. These are the factors which relate the indentation values of figure 13 with those of figure 12. The interesting facts brought out in table 4 are that (1) the ratios for a given indenter decrease for the more elastic materials, (2) the difference in ratio for different indenters is small, for a given material like rolled gold, and (3) the ratios decrease (the apparent elastic recovery is greater) for the more elastic materials with obtuse indenters. It must be noted that w_1/w is not a direct measure of the elastic return across the transverse diagonal of indentations of the ridged and sinking-in types. In order to determine the actual recovery at surface level of a ridged indentation in soft-rolled copper, the recovered width was measured after removal of the ridge. This gave a ratio of recovered width to calculated width of 1.00 (no recovery) instead of a determined w_1/w value of 1.14. Also, the height of the ridge of an indentation by indenter 5 in steel gage 1 was measured by an interference method and the unrecovered width at the top of the ridge was calculated, giving a ratio of recovered to unrecovered width at that level of 0.87 (13-percent recovery) instead of a w_1/w ratio of 0.98. Although these tests were not extended to other specimens, they show the practicability of obtaining the actual transverse recovery of indentations—a factor which appears to greatly influence the w_1/w values.

TABLE 4.—*Ratio of measured width to calculated width w_1/w with different indenters in various specimens*

Indenter	w_1/w for different specimens								
	Rolled gold	Rolled platinum	Rolled copper	Steel *C 25*	Steel *C 47*	Steel gage 1	Steel gage 2	Steel *C 65–67*	Glass med. flint
7	1.32	1.28	1.31	1.17	1.22	1.13	1.06	1.00	0.90
1	1.31	1.30	1.31	1.19	1.17	1.03	0.95	0.92	.82
8	1.34	1.28	1.25	1.12	1.10	0.99	.92	.89	.80
4	1.34	1.29	1.24	1.15	1.13	1.00	.92	.88	.78
3	1.32	1.27	1.22	1.13	1.12	0.99	.91	.88	.80
6	1.30	1.25	1.22	1.08	1.03	.93	.87	.85	.77
2	1.29	1.27	1.17	1.09	1.07	.91	.84	.83	.74

Heyer[12] offers an explanation for the differences commonly observed in the contours of Brinell indentations which is based upon the relative strengths in shear and compression of the specimens. With indenters having different angles, the applied stresses will doubtlessly be distributed to give differences in the effective frictional forces, in the deformation of the diamonds, in the strain-hardening of the specimens, in the amount of material disrupted, and in the elastic recovery of the indentions. The integration of the forces acting results in the final form and size of the indentations, and it is conceivable that the w_1/w ratio may have physical significance in relating

[12] Robert H. Heyer, Proc. Am. Soc. Testing Materials **37**, pt. 2, 119 (1937).

angular shapes of the indenters to the distribution of stresses in indenters and specimens, which produces the final indentations.

The authors are impressed with the orderly arrangement of the w_1/w values in table 4 and believe that further study with carefully selected and more uniform materials will lead to a better understanding of the factors involved in correlating the indentation numbers obtained on the basis of unrecovered projected area for the different indenters. The possibility of associating these w_1/w ratios with the work-hardening capacity of a material also presents a field for investigation.

V. SELECTION OF DIMENSIONAL BASIS FOR COMPUTATION

From preceding considerations it is evident that, with a given indenter, indentation scales can be derived which are based upon the ratio of applied load to any dimension (linear, surface, or volume) of recovered or unrecovered indentations. The authors prefer to define the indentation number as the ratio of the applied load to the *unrecovered* projected area, thereby incorporating both elastic and plastic deformation in the test.

Linear dimensions and volumes of indentations were rejected as bases of computation because, although these gave agreement for a given indenter under varying loads when the square of linear dimensions or the 2/3 power of volumes was used, the results with different indenters could not be correlated. Areas (lateral or projected) appear to be more directly related to applied loads than either penetrations or volumes.

It should be understood that indenters which produce circular or square-based indentations furnish measurements of recovered (permanent) deformation only. With the elongated pyramidal indenters all dimensions of an unrecovered indentation can be obtained from the shape of the diamond and the measured length of an indentation. An added measurement of the width, combined with the measured length, yields the recovered projected area but no dimension which requires knowledge of the recovered depth. The ratio of the recovered and unrecovered widths or projected areas gives an estimate of the magnitude of the elastic deformation; and, when investigating elastic materials, it seems instructive to state this ratio in addition to the indentation number. The use of areas which depend upon the elastic recovery of a material is rejected as a method of expressing the results of indentation tests because this associates an applied load with an area other than that involved at the time the load was applied. Furthermore, an unrecovered area is chosen to express the indentation number because it seems to afford the most rational interpretation of the results, placing as it does vastly different materials such as rubber, copper, glass, and hardened steel in some logical order; whereas no reasonable sequence results from the use of recovered areas.

For expressing the results of indentation tests in terms of areas, the load may be related to either the lateral or the projected area, which for a pyramidal indenter differ merely by a factor, namely the cosine of the angle between them. Of these two areas, the projected is favored here because the measured load is applied normal to that area, and that load is equal to the vertical component of the unknown forces reacting on the lateral faces. With lateral area the unknown force normal to the faces of the indenter would seem to be the one to use. For those materials in which the resultant of the reacting forces is normal to the faces of the indenter, the normal force will, of course, be greater than its vertical component; for materials in which the resultant of the reacting forces is not perpendicular to the indenter faces, the normal component may be greater or, conceivably, even less than the vertical component. Consequently, indentation numbers which are obtained by dividing the applied load by the lateral area will not be a true measure of resistance to indentation.

Tests based upon the unrecovered projected area (fig. 12) show that indentation numbers obtained with all the pyramidal indenters used have about the same value for materials like rolled gold and copper, which have little if any elastic recovery; whereas greater numbers are obtained for more elastic materials with acute indenters than with obtuse indenters—the latter giving the greater transverse elastic recovery. Figure 12 shows that the spread in indentation number with indenters having different angles is greatest for the materials which exhibit the greatest elastic recovery. Any attempt to analyze theoretically these divergences requires exact knowledge of the distribution of stresses within the specimens, and this distribution is, in turn, affected by the strength properties of the materials. Such analysis is beyond the scope of this investigation.

VI. SELECTION OF AN INDENTER FOR GENERAL USE

Results of the experimental work with elongated pyramidal indenters of various angular shapes indicated that an indenter might be selected that would be satisfactory for testing all materials to which indentation tests are applicable. The advantage of adopting a standard indenter for all tests is that it eliminates troublesome conversions of indentation numbers from one scale to those of some other scale. Since indentation numbers with the same indenter were found to be quite independent of the load applied, then, by adopting a standard indenter and by varying the load on this indentor to suit test conditions, all materials and specimens are placed in a single indentation scale.

In selecting the angles of an indenter for general use, consideration was given to sensitivity, definition of the indentation, possibility of longitudinal elastic recovery, and adaptability for use in different materials. The most sensitive indenters, table 5, column 6, are those which give narrow, shallow indentations. Sensitivity, however, is necessarily limited by two considerations: First, that results with such tools are greatly affected by surface irregularities, thus requiring excellent surface finish and great care in the preparation of specimens to avoid surface hardening; and, second, that lateral contraction of indentations for l/w ratios exceeding 10 gives terminations of the longitudinal diagonals (right central photograph, fig. 6) for highly elastic materials which are not fully resolved in the microscope. The definition is greatly improved by increasing the width relative to the length. For a constant transverse angle this may be accomplished by decreasing the included longitudinal angle, giving increased penetration. However, the reduction in sensitivity and the possibility of elastic recovery in a longitudinal direction makes it advisable to use l/w ratios greater than 5. Of great practical importance in the selection of an indenting tool is its adaptability for use in different

TABLE 5.—*Relationship of indenter constants and measured lengths and calculated penetrations for different indenters with a 4-kg load in steel C 25*

Indenter	Included angles				Length / Width	Length / Penetration	Values with 4 kg for C 25	
	Longitudinal		Transverse				Length (measured)	Penetration (calculated)
(1)	(2)		(3)		(4)	(5)	(6)	(7)
	deg	*min*	*deg*	*min*			*μ*	*μ*
1	175	20	118	36	14.6	49.1	645	13.1
2	174	53	134	15	9.4	44.8	535	11.9
4	173	52	126	12	9.5	37.3	525	14.1
7	170	0	100	36	9.5	22.9	515	22.5
8	172	32	129	40	7.2	30.6	455	14.9
3	171	42	126	36	6.9	27.6	450	16.3
6	170	44	136	0	5.0	24.7	390	15.8
Vickers	148	7	148	7	1.0	7.0	[a] 167	[a] 23.9

[a] Computed from Vickers number=265 for steel *C 25*.

materials. To illustrate: Indenter 2 (134° transverse angle) gave less shattering in glass with a load of 2 kg than did indenter 7 (100° lateral angle) with 0.2 kg; yet, although a broad angle gives better results in brittle materials, it is not suitable for materials which can not be readily polished to the degree of refinement obtainable with glass. From these considerations, the following shape was selected to give the best weighted performance:

Included longitudinal angle	172°30′
Included transverse angle	130°0′
Constant for projected area	7.03×10^{-2}
Constant for lateral area	7.77×10^{-2}
Ratio of length to width	7.11
Ratio of length to penetration	30.5

If from the standpoint of simplicity and accuracy of production and calibration it is better to define the shape of the standard indenter in terms of face angles, then dihedral angles of 130° between opposite faces and azimuthal angles of 16° and 164° between adjacent faces are recommended. For this shape the edge angles become 172°34′25″ and 130°25′40″, which differ but slightly from the first specification.

VII. COMPARISON OF THE INDENTATION SCALE OF INDENTER 8 WITH BRINELL AND VICKERS SCALES

Indentation numbers were determined for the standard specimens with indenter 8, which approximates the selected shape very closely. Brinell and Vickers numbers were obtained for the same specimens through the courtesy of the Engineering Mechanics and the Mechanical Metallurgy Sections of the National Bureau of Standards. The results are given in table 6. Indentation numbers, I, with indenter 8 are 20 percent greater than corresponding Brinell numbers for rolled copper and agree with the Brinell numbers for steel, *C 65–67*. Numbers with indenter 8 are 13 percent greater for rolled copper and 12 percent less for steel, *C 65–67*, than the corresponding Vickers numbers. In view of the differences in the shapes of the indenters and in the bases of computation, greater differences in indentation numbers could well be expected.

Indentation numbers were determined with indenter 8 for many materials which are not commonly tested by indentation methods. Numbers for several widely different materials are listed in table 6. Where a single indentation number is given, the number is the average of several determinations on one or more specimens which in some cases differed appreciably. The corresponding Mohs hardness numbers for some of the specimens are given in brackets.

TABLE 6.—*Comparison of indentation numbers with indenter 8 and Brinell and Vickers numbers for the same specimens*

Specimen	Brinell test			Vickers number	Indenter 8. Indentation number, *I*
	Conditions of test		Brinell number		
	Ball	Load (30 sec)			
		kg			
Rockwell *C* 65-67	10 mm, Carboloy	3,000	780	894	791
Gage 2	do	3,000	745	848	779
Gage 1	do	3,000	611	655	637
Rockwell *C* 47	10 mm, steel	3,000	456	493	496
Rockwell *C* 25	do	3,000	241	265	276
Rolled copper	1/16 inch, steel	15	104	111	125
Rockwell *B* 7-9	10 mm, steel	500	52.8	58.2	59.2

Specimen	*I* (*indenter 8*)
Pitch (for optical polishers)	1–22
[2] Gypsum	32
[3] Calcite	135
[4] Fluorite	163
Flint glass	180–390
[5] Apatite, parallel to axis	360
[5] Apatite, perpendicular to axis	430
Crown glass	420–470
Fused quartz	475
[6] Albite	490
[6] Orthoclase	560
[7] Crystaline quartz, parallel to axis	710
[7] Crystaline quartz, perpendicular to axis	790
Nitrided annealed high-speed steel	800
Chromium plate	850–900
Carboloy	1,050
Nitrided hardened high-speed steel	1,100
[8] Topaz	1,250
Alundum	1,635
Silicon carbide	2,000
Boron carbide (molded)	2,230
[10] Diamond	8,000–8,500

VIII. FIELD OF APPLICATION OF THE INDENTER

In considering the performance of the diamond-based pyramid indenter, the chief characteristic which warrants its introduction among other indenters is its sensitivity. Although its use is not restricted to small loads, loads of 0.5 kg are sufficient to give indentation lengths of 100 μ in the hardest steel tested; and, with indentations of this length, differences in indentation numbers greater than 2 percent in well-surfaced specimens may be attributed to nonuniformity of the specimen. The use of light loads permits the satisfactory testing of many brittle materials which could not be tested satisfactorily by other indentation methods, and the resulting indentation numbers for these materials fall within the range of present indentation scales for metals. In view of the generally satisfactory results

FIGURE 14.—*Indentations in a quenched, high-purity iron—1.14-percent-carbon alloy (magnification, ×250).*

For indentations 1 to 9 a load of 100 g was used. Nos. 1, 2, and 9 are in areas where ferrite, pearlite, and cementite predominate. Nos. 3 and 8 are in troostite (fine pearlite). Nos. 4, 6, and 7 are in martensite. No. 5 shows an indentation in an area of troostite about 25 μ in diameter entirely surrounded by martenite. No. 10 was made in martensite with a 50-g load. The indentation numbers ranged from 190 for the soft constituents to 720 for the martensite.

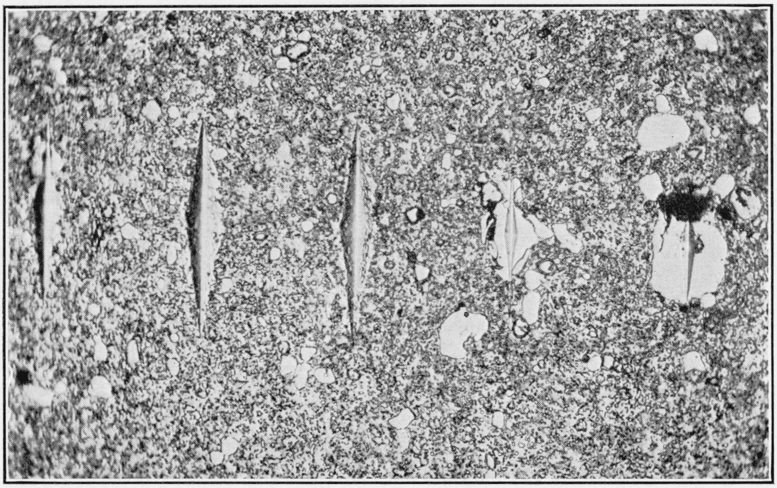

FIGURE 15.—*Indentations in a molybdenum-tungsten-cobalt steel containing large carbide particles (magnification, ×500).*

The indentation numbers were about 230 for the matrix and 1,430 for the carbide particles.

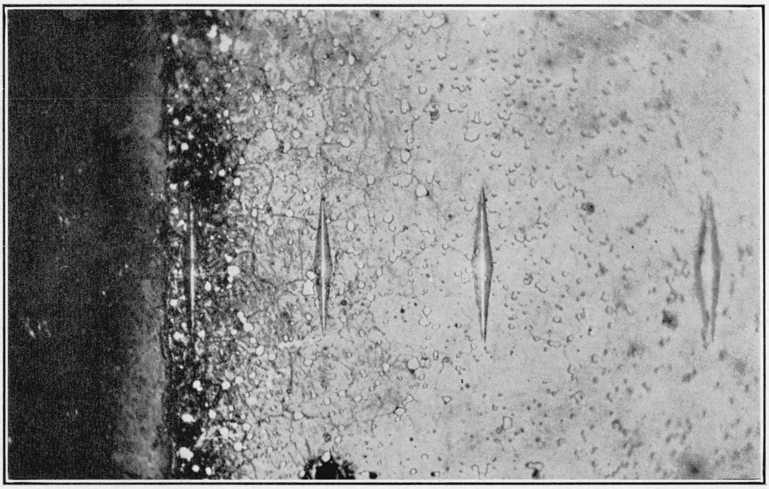

FIGURE 16.—*Indentations in a specimen of nitrided hardened molybdenum-tungsten high-speed steel cut perpendicular to the nitrided surface (magnification, ×500).*

Indentations made at positions 4 μ to 7 μ from the edge of the material partially cracked out. At distances from 10 μ to 25 μ from the edge, the indentation numbers were about 1,100, which agrees with measurements made normal to the nitrided surfaces of similar specimens. For greater distances the numbers decreased progressively until 780 (that of the original matrix) was reached at positions more than 60 μ from the edge.

obtained with present forms of indenters in testing large specimens of materials which do not shatter under heavy loads, it would appear that the immediate field of application for the diamond-based pyramid indenter would be the testing of small specimens and materials which shatter under heavy loads but will withstand application of the light loads required for this tool. Glasses, dental plastics, enamels, and porcelains have been tested satisfactorily with this indenter; and it seems equally well adapted to the testing of electrodeposits and thin sheet metal. Although no extensive study has yet been made of minimum thicknesses which may be tested, useful information was obtained from tests of layers 0.0005 in. thick.

The indenter has recently been applied to the microtesting of different areas of a quenched, high-purity iron—1.14-percent-carbon alloy (fig. 14)—furnished by T. G. Digges of the Metallurgical Division;[13] to a molybdenum-tungsten-cobalt steel (fig. 15) which contains large particles of carbide; and to a section of a nitrided specimen of hardened molybdenum-tungsten steel (fig. 16). The last two specimens were furnished by Ralph G. Kennedy, Jr., Cleveland Twist Drill Co.

In the light of the experience gained in the use of the elongated pyramidal indenter, more specific knowledge of the load requirements for accurate testing has been obtained. A range of 0.1 to 2.0 kg appears satisfactory for testing materials within the indentation range of 5 to 2,000 on this scale when the size of the specimens permits the use of these loads. For microindentation testing of exceedingly small or thin specimens, it seems desirable to have a sensitive mechanism that will apply light loads to the indenter, either progressively or in steps of 0.02 kg from 0.0 to 0.1 kg, and in larger steps from 0.1 to 0.5 kg. The use of loads exceeding a few kilograms with this indenter would appear advantageous only in testing resistant materials in which the surface finish of the specimens may not be commensurate with accurate testing with light loads and in integrating the mass hardness of heterogeneous materials.

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[13] J. Research NBS 20, 571 (1938) RP1092.