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CORRELATION OF VICKERS HARDNESS NUMBER, MODULUS OF ELASTICITY, AND THE YIELD STRENGTH FOR DUCTILE METALS*

by

Emil Arbtin, Jr. and Glenn Murphy

I. INTRODUCTION

Hardness tests are widely used for determining comparative hardness numbers for metals, because of their simplicity and rapidity of operation. If appropriate charts or equations are known a given hardness number can be converted to other hardness numbers or to some of the mechanical properties.

There are many definitions of hardness. Aristotle (384-322 B.C.) defined the word "hard" as that which does not cede to penetration through its surface (1). Huygens in his Treatise on Light published in Leyden in 1690 discussed hardness and mentioned that it varies with the direction on the surface of crystals (9, p. 99). Colonel Martels in 1893 made a report to the French Commission on material testing (12, p. 11). In this paper he defined hardness of metals as the resistance to displacing the molecules at the surface and he measured hardness by the work required to displace a unit volume. This definition, he remarks, is special and applies to malleable materials which can have their molecules displaced without rupture. In the paper referred to, Martel quoted the definition of hardness given by Osmond (12, p. 14) which reads: "Hardness is that property possessed by solid bodies, in a variable degree, to defend the integrity of their form against causes of permanent deformation, and the integrity of their substance against causes of division." Hardness has been defined by various writers as resistance to abrasion, cutting, or indentation, and many methods have been devised to determine hardness by these means.

Indentation hardness testing is important commercially in that it is widely used for the determination of the suitability of a material for a certain purpose, maintainance of the uniformity of a product, and, because of the fact that it is non-destructive in nature, materials so tested can be used in service.

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*This report is based on a M. S. thesis by Emil Arbtin submitted June, 1953.

The indentation hardness testing method was used in determining the hardness of metals reported in this paper. The Vickers method of indentation hardness testing was chosen because it is the hardness test most used in research today, and the method of testing has been standardized by various organizations.

The purpose of this thesis was to determine whether or not a relationship exists among a particular type of indentation hardness number, the Vickers hardness number, yield strength, and modulus of elasticity and to ascertain the effect of magnitude of load and time of load application on the Vickers hardness number.

II. REVIEW OF LITERATURE

A. History of Some Types of Hardness Tests

1. Indentation

Reaumur (1683-1757), who has been called the "father of hardness measurement," seems to have been the first to establish a means of measuring hardness, using the method of pressing the edges of two right angled prisms made of two different materials into one another (17). Since the pressure was the same in the two materials the results gave the relative hardness.

The physicist P. Van Musschenbroeck (1729-1756) studied hardness, according to Hugueny (8), with an apparatus consisting of a knife the handle of which was struck by an ivory ball. The number of blows required to cut through the material divided by its specific gravity was taken as a measure of its hardness. Van Musschenbroeck was mostly interested in the study of splitting woods, and the test was naturally suited to his needs. He also studied the hardness of some of the common metals, but his study was devoted rather to cleavage than to hardness.

In 1856 a Commission of American Artillery Officers conducted experiments on the strength of metals for the manufacture of cannon (5). This Commission determined hardness by loading a pyramidal cone with a weight of ten thousand pounds and measuring the volume of the impression. Their hardness unit was an impression whose volume was one-third of a cubic inch. An impression which had a volume of one-half the standard, or one-sixth of a cubic inch, was given the value two, etc. The smaller the impression value the greater the hardness.

A year or two later, in 1857-1858, Grace Calvert and R. Johnson (3) devised a hardness tester. This machine was of the penetrator type, the penetrator being a truncated cone made to definite dimensions. The depth of penetration was measured by a scale equipped with a vernier. The depth was fixed at 3.5 mm. and the load required to penetrate this depth was called the hardness number. The work of these investigators was mostly confined to the softer metals. In their hardness scale, cast iron was taken as the unit.

In 1873 Bottone (2) also measured the hardness of malleable metals by a penetration test. For fragile substances which could not be tested by penetration method a wear test was substituted. For this wear-hardness test Bottone employed a soft iron disc rotating at a given velocity which was pressed against the object tested with a definite pressure. He measured the time required to cut a certain depth and this time was taken as being proportional to hardness.

In 1879 A. Föppl (1854-1924) following in the path of Reaumur and probable also inspired by the work of H. Hertz (1857-1894) merely changed the prisms used by the latter (7) for two semi-cylindrical bars that had their axes placed at right angles to one another. The bars were then pressed together. By measuring the area of contact of the flattened surfaces and dividing the load by the area, he obtained the hardness (6).

The Swedish metallurgist John August Brinell, then chief engineer of the Fagerrta Iron and Steel Works in Sweden, showed the now well-known hardness tested bearing his name at the Paris Exposition of 1900. The method used by Brinell consisted in pressing a hard steel ball into the surface of the metal to be tested. By measuring the dimensions of the impression, then calculating the surface area and dividing the load by this area, the hardness number is found. As the load is usually measured in kilograms while the area is in square millimeters, the Brinell hardness number is therefore the load in kilograms per square millimeter required to deform the material under test.

The Rockwell hardness tester is different from the Brinell hardness tester in that a minor load is applied to the penetrator in order to have the penetrator firmely seated on the surface to reduce the effect of surface condition. Next a major load is applied for a controlled length of time. The Rockwell number is based on the difference between the depth of penetration at major and minor loads. Details are given in Table 1 for various Rockwell tests and others.

The Vickers hardness tester is similar in method to the Brinell test. A predetermined load is impressed at a point upon the specimen. The loaded indenter point, a square based diamond pyramid, is allowed to descend upon the specimen gradually, and at a diminishing rate. This

Table 1

Details of Some Hardness Tests*

Type of Test	Designation of Scale	Used for	Major Load (kg.)	Type of Penetrator Used	Recommended Time of Test (sec.)	Minor Load (kg.)
Vickers		Metallic materials	1-120	Square based diamond pyramid	10	None
Brinell		Ferrous	3000	10 mm ball	10	None
Brinell		Non-ferrous	500	10 mm ball	30	
Rockwell	A	Cold rolled strip steel, case hardness steel, nitrided steel	60	Brale	See note below	10
Rockwell	B	Standard	100	1/16" ball	See note below	10
Rockwell	C	Standard	150	Brale	See note below	10
Rockwell	D		100	Brale	See note below	10
Rockwell	E	Die castings	100	1/8" ball	See note below	10
Rockwell	F	Annealed brass	60	1/16" ball	See note below	10

Note: The Rockwell machine is provided with a means of regulating the rate of application of the load. The machine should be adjusted so that when no specimen is in the machine at least five seconds are consumed in the travel of the weight from its initial to its final position, using the one hundred kilogram load. If the 150 kilogram load is used, the time should be four seconds as a minimum.

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*Reproduced from Murphy, G. and Arbtin, E. Rockwell and Vickers Hardness of Ames Thorium, p. 6. U.S. Atomic Energy Commission. Iowa State College-316. 1953.

application and the removal of the load, after a predetermined interval, are controlled automatically. The internal mechanism of the Vickers instrument consists mainly of a cam operated by a weight. The speed of rotation of this cam is controlled by an oil dashpot, and the movement applies the load to the diamond indenter. This cam applies, removes, and controls the duration of the load. The Vickers hardness number is found by dividing the applied load by the surface area of the impression. Tables are available that give the hardness number as a function of applied load and diagonal of the impression which is easily measured. The hardness numbers obtained with the Vicker pyramid diamond, according to Williams (20, p. 451), are practically constant, irrespective of the load applied. The Vickers and Brinell hardness values on steel are practically identical up to a hardness of about three hundred. At higher hardness values the Brinell falls progressively lower than the Vickers number and is not reliable above about six hundred Brinell, even with specially hardened balls. This irregularity is caused by flattening of steel balls under the heavy loads required for testing hard materials whereas the diamond shows no distortion.

2. Scratch

C. Huygens (1629-1695) suggested that the optical properties of Iceland spar could be accounted for by supposing the crystal structure as being composed of flat spheroidal molecules, and that at the surface of the crystals the flattened spheroids were arranged directionally like the scales on a fish. Therefore if a sharpened edge is moved in the direction of the scales, it will slip over them, but if it is attempted to move the edge against the scales, it will catch against them and slipping is impeded. He notes this same effect in applying the scratch method to the surface of Iceland spar. The scratch method is in fact one way of demonstrating the direction in which the crystal is oriented (9, p. 99).

F. Mohs (1773-1839) devised a scratch method of hardness testing that is still in use by minerologists today (15). Mohs's scale was divided into ten degrees of hardness; the classification is shown in Table 2. Its primary drawback is that the intervals are not well spaced in the higher ranges of hardness, and also the inclination and orientation of the scratching point may effect the results. The procedure for making a Mohs's test is to apply the specimen to the hardest Mohs's mineral and then work downwards through the scale until the member in the scale which definitely allows itself to be scratched is reached.

Seebeck in 1833 invented the sclerometer, a hardness testing instrument which carried a loaded point on which rested a weight while the whole was given a movement of translation producing a scratch (8). With this type of instrument one may measure hardness in three ways:

Table 2

Mohs's Scratch Hardness Scale

Material	Mohs's number
Talc	1
Gypsum	2
Calc spar	3
Fluor spar	4
Apatite	5
Feldspar	6
Quartz	7
Topaz	8
Sapphire	9
Diamond	10

(1) by finding the minimum weight necessary to produce a scratch visible under certain conditions of illumination, (2) by measuring the tangential force required to pull a loaded scratch point, or (3) by measuring the width of the scratch produced by a certain load. There have been several modern machines developed to determine hardness by these three methods.

3. Dynamic

The dynamic method of hardness testing was developed comparatively recently and has achieved comparatively little industrial importance yet. In 1893 Lieutenant Colonel Martel (12, p. 11) made a report to the French Commission on material testing. In this report Martel sets down the characteristics of dynamic hardness testing. His method of hardness testing consisted in striking a blow by means of a falling tup indenter on the body for which the hardness was to be determined and measuring the volume of the permanent deformation. Martel showed that the volume of the indentation produced by the falling tup was proportional to the height of fall and the mass of the tup and independent of the shape (21). The Shore Scleroscope is a modern instrument very similar to the Martel instrument. In this method a small steel or diamond tipped weight is dropped on the specimen from a fixed height, and the height of rebound is measured.

B. Hardness Relationships

1. Hardness related to hardness

At present the hardness number determined by one test is not directly convertible analytically to a hardness number of a different test. Each type of hardness test is influenced differently by the properties of the material being tested. Different loads, different shapes of penetrators, homogeneity of the specimen and cold working properties of the metal all complicate the problem (11). The data for hardness conversion charts at present must be found by testing and a different chart must be made for each type of metal, for example steel, brass, and thorium. Figure 1 shows the general shape of various conversion curves and illustrates the fact that a hardness conversion chart or graph for one material can not be used for other metals.

2. Hardness related to strength

Little work has been done on relating hardness to strength for metals with the exception of steel. In 1930 the National Bureau of Standards published a paper which gave empirical formulas, with errors to be expected of less than fifteen per cent, for determining the tensile strength of steel from Rockwell B, Rockwell C, and Brinell hardness numbers (16). The report stated that no discernible relationship was found between the tensile strength of non-ferrous metals and their indentation number.

III. INVESTIGATION

A. Objectives

The objects of this investigation were to determine:

1. Whether or not a relationship exists between the yield strength, modulus of elasticity, and Vickers hardness number for various metals.
2. The effect of time and load on the Vickers hardness number for several different metals.

B. Hypothesis

Mr. Forrest E. Cardullo gave what seems to be one of the clearest expositions on the subject of hardness in Mechanical Engineering, October 1924 (4, p. 638). Mr. Cardullo said:

> On reviewing the attempts which have been made to measure hardness, we find that the methods employed do not give results which are a dimensional property of the material. That is, these results cannot be expressed in a rational term which is the product of two or more of the real powers of the fundamental physical units of length, time, force, and mass. For instance,

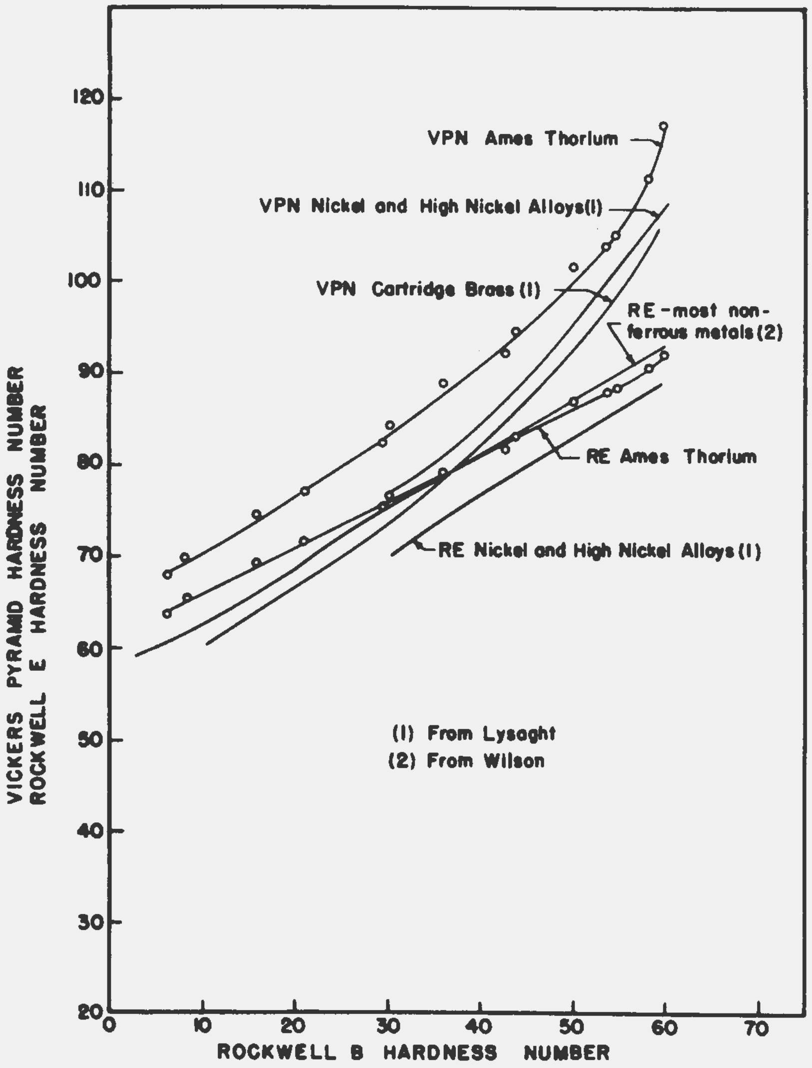

FIG. I HARDNESS CONVERSION CHART FOR VARIOUS METALS

Reproduced from Murphy, G. and Arbtin, E. Rockwell and Vickers Hardness of Ames Thorium, p. 10. U.S. Atomic Energy Commission. ISC-316. 1953.

Mohs's scale of hardness gives a list of ten minerals, each of which can be scratched by the next harder and can scratch the next softer. This is not a method of measuring hardness, but merely a method of comparing the relative hardness of two substances differing widely in hardness.

While we have no accepted definition for hardness . . . still it may not be impossible to identify it with some dimensional property of material. The following line of reasoning may serve to clear up the situation to some extent.

When two bodies of the same size and form, and so disposed that their plane of contact is a plane of symmetry between them, are pressed together, the stresses and distortions produced in each will be equal, if they are of identical materials. The simplest case is of course where two equal spheres are pressed together. If the spheres are of identical physical properties, the area of contact between them will be a plane surface and circular in form. The bodies will be equal in hardness and the stresses and temporary and permanent deformations produced will be the same in each. If we take two spheres otherwise equal but of unequal elastic moduli and press them together, the area of contact will be a limited portion of a surface of revolution, and concave toward the center of the rigid sphere . . . . . The normal pressure at any point in the surface of contact will be the same for both spheres. If the elastic limit is the same for both materials and the pressure is increased till the elastic limit is exceeded, both spheres will be permanently deformed; but it is obvious that the one having the lower modulus of elasticity will be deformed more than the one having the higher modulus of elasticity.

Similarly, if two spheres of unequal moduli of elasticity are pressed upon a third one of much higher modulus of elasticity and elastic limit than either of the first two, the one having the lower modulus of elasticity will be deformed the most.

From this the writer concludes that one of the dimensional properties of which hardness is a function is the modulus of elasticity, and the higher the modulus of elasticity of a material, the greater its hardness will be.

Let us return to our first line of reasoning and consider two spheres of equal moduli of elasticity but of unequal elastic limits, to be pressed together. Until the elastic limit of the weaker sphere is reached, the area of contact remains a plane circle. As soon as the elastic limit of the weaker sphere is passed, the area of contact ceases to be a plane circle and becomes concave toward the center of the stronger sphere . . . . When the pressure is removed, if the elastic limit of the stronger sphere has not been exceeded, it will return to its original form, while the weaker one will be permanently deformed. If the elastic limit of both materials has been exceeded, both of the spheres will be deformed, the weaker one, however, suffering the greater deformation. Hence we may conclude that the hardness of a material is a function of its elastic limit, and more specifically of its compression elastic limit.

If we assume that the more rigid sphere has the lower elastic limit, we will observe the following phenomena as the pressure is increased:

Until the elastic limit of the weaker sphere is reached, the area of contact will be a curved surface concave toward the center of the more rigid but weaker of the two spheres. As the pressure increases, the elastic limit will finally be reached at the center of the surface of contact. Since the material there is supported by the surrounding material, the stresses are partly hydrostatic and partly shearing in their nature, and permanent deformation will not occur until the shear elastic limit has been passed. Because of its greater deformation this point may be reached first in the case of the stronger but less rigid sphere.

It is possible that the behavior of the two spheres under the conditions of this experiment will not be controlled exclusively by their respective elastic limits and moduli, but will also be dependent on the forms of that portion of their stress-strain diagrams lying just beyond the elastic limit. In such a case the problem of making hardness a function of dimensional properties becomes rather hopeless. Furthermore it will probably be impossible to obtain consistent results when attempting to arrange a number of materials in a definite order of hardness when each is tested against all of the other, which is the simplest of all the problems in connection with the determination of hardness.

The logical solution of the difficulty seems to be to take the principal dimensional properties involved in the idea of hardness, to write an equation of rational form connecting these properties with a numerical value for hardness, to determine experimentally whether this equation is consistent, and the value of its constants, and to accept this equation as the definition of hardness. It is obvious that the principal dimensional properties affecting the hardness of a homogeneous material are its elastic limit and modulus of elasticity. The simplest form of equation that we can write connecting hardness with these properties is

$$H = C\,E^{m}L^{n}$$

where H = numerical value of hardness
C = a constant
E = modulus of elasticity
L = compression elastic limit
m, n = small positive real indices.

If now we prepare spheres of a number of different materials and investigate their behavior under the sort of test just described, we may determine the values of m and n, and obtain a rational definition of hardness. It is probable that the value of both m and n lie pretty close to unity.

The author of this paper proposes that a similar type of phenomenon takes place when a rigid indenter is pushed into a ductile metal. That is when the indenter is pushed into a specimen and the resulting stresses developed in the material of the specimen do not exceed the elastic limit of the material, there will be no indentation in the specimen when the load is removed from the indenter. If the elastic limit of the material is exceeded there will be plastic flow in the material under the indenter and when the load on the indenter is released there will be an indentation left in the specimen. For a given depth of penetration and shape of indenter the final depth and shape of the indentation will be dependent on the modulus of elasticity and elastic limit of the material. Therefore it is assumed that the main properties of a homogeneous material that effect the hardness are the modulus of elasticity and elastic limit.

C. Method of Procedure

1. Materials

In considering the characteristics of the materials to be tested the following were taken into account:

1. The desirability of more than one type of metal in each modulus of elasticity grouping.
2. A wide range of strengths in each modulus of elasticity grouping.
3. The availability of the metals.

It was decided to use twenty-one different metals in three modulus of elasticity groupings in the tests. This number included four samples of aluminum, three of brass, three of copper, one of magnesium, five of steel, one of tantalum, one of tin, and three of zinc.

2. Apparatus

There were two primary pieces of apparatus used in the tests. They were the Vickers pyramid hardness testing machine and a sixty thousand pound capacity Baldwin Universal testing machine equipped with a microformer stress-strain recording device.

3. Conduct of tests

The hardness test specimens were prepared for testing by wet surface grinding to a fine finish, two parallel flats on each sample. The test surface was carefully cleaned with a soft cotton cloth prior to testing. The test loads used varied from one to fifty kilograms depending on the hardness of the particular specimen. The times of load application used in testing were ten, twenty, and thirty seconds. At one load and time of load application, for each specimen, ten hardness tests were made. The average of two hardness tests was found for each of the other combination of time and load used. A total of eight hardness number averages was found for each specimen except tin. The low hardness of the tin specimen made it impossible to use a load higher than two kilograms in testing.

The tensile test specimens were made with a 0.252 inch diameter and sufficient length for the use of a one-inch gage length microformer extensometer. The tensile test was conducted with an upper crosshead velocity of three-thousands of an inch per minute until a unit strain of at least fifteen-thousands had been achieved, then the crosshead velocity was increased to forty-thousands of an inch per minute for the remainder of the test. The crosshead velocity was measured by timing the displacement of the cross-head, which was measured by a dial micrometer. The tensile properties computed from the test results were the modulus of elasticity, the yield strength (0.2% offset), and the ultimate strength in pounds per square inch.

IV. RESULTS AND DISCUSSION

The results of the tensile and hardness tests are given in Tables 3 and 4 respectively. In Figures 2, 3, and 4 the ultimate and yield strengths are shown plotted against the corresponding Vickers hardness number. The Vickers hardness number used in plotting was the average of ten hardness tests. Three figures were used in plotting the data in order that the data of each modulus of elasticity group could be shown together and to reduce the confusion resulting from a large number of plotted points. The mean line shown in each figure was obtained by the least-squares method. In the analysis it was assumed that the Vickers numbers were correct and the ultimate strength numbers were subject to error. The equation of the mean line shown in each figure was found to be:

1. Ultimate strength = -626 + 445(VPN) for materials with a modulus of elasticity approximately equal to 10,000,000 psi.

Table 3

Tensile Test Data

Material	Modulus of elasticity (X 10^6 psi.)	Yield strength, 0.2% offset (X 10^3 psi.)	Ultimate strength (X 10^3 psi.)
Aluminum			
Commercially pure	10.3	3.4	5.6
2-S	10.0	20.4	22.9
17-ST[a]	10.4	37.0	60.0
24-ST-4	10.4	47.5	68.0
Brass			
180-S[a]	17.0	22.5	52.0
Screw stock	13.2	42.4	62.9
180-H[a]	17.0	68.0	101.0
Copper			
Commercially pure[a]	17.0	5.0	32.5
159-S[a]	17.0	17.0	45.0
Type unknown	16.5	49.3	49.9
Magnesium			
Commercially pure	6.5	3.4	11.5
Steel			
Armco	26.0	37.4	47.0
1020	32.8	69.0	79.9
1045	30.5	60.4	100.4
1095	30.3	92.4	167.0
1.3% Carbon	30.0	49.3	111.7
Tantalum			
Commercially pure	26.5	66.0	67.5
Tin			
Commercially pure	6.0	1.6	2.4
Zinc			
Hot Rolled[a]	10.0	10.2	18.7
Zamak 3[a]	11.5	23.0	34.0
Zamak 5[a]	13.0	31.7	40.7

[a] Adapted from Murphy, G. Properties of Engineering Materials. 2nd ed. Scranton, Pennsylvania, International Textbook Co. 1947. Hardness specimens were from identical rods and plates as tensile specimens in reference cited.

Table 4

Vickers Hardness Number Data

Material	Load (kg.)	Time (sec.)	Vickers pyramid hardness no.	Standard deviation (VPN)
Aluminum				
Commercially pure	1.0	10.0	22.4	
	2.5	10.0	19.2	0.402
	5.0	10.0	17.4	
	2.5	20.0	18.3	
	5.0	20.0	17.1	
	1.0	30.0	21.5	
	2.5	30.0	18.0	
	5.0	30.0	17.1	
2-S	2.5	10.0	41.0	
	10.0	10.0	42.5	0.947
	20.0	10.0	41.8	
	2.5	20.0	39.6	
	20.0	20.0	41.1	
	2.5	30.0	40.2	
	10.0	30.0	41.2	
	20.0	30.0	41.7	
17-ST	2.5	10.0	143.0	
	20.0	10.0	133.0	1.28
	50.0	10.0	131.5	
	2.5	20.0	139.0	
	20.0	20.0	134.0	
	2.5	30.0	140.0	
	20.0	30.0	132.8	
	50.0	30.0	130.8	

Table 4 (con't)

Material	Load (kg.)	Time (sec.)	Vickers pyramid hardness no.	Standard deviation (VPN)
(Aluminum con't)				
24-ST-4	2.5	10.0	170.0	
	20.0	10.0	158.8	2.45
	50.0	10.0	157.5	
	2.5	20.0	162.0	
	20.0	20.0	161.0	
	2.5	30.0	167.0	
	20.0	30.0	158.5	
	50.0	30.0	158.0	
Brass				
180-S	2.5	10.0	150.0	
	20.0	10.0	139.5	12.15
	50.0	10.0	151.5	
	2.5	20.0	156.0	
	20.0	20.0	141.7	
	2.5	30.0	148.0	
	20.0	30.0	137.5	
	50.0	30.0	142.0	
Screwstock	2.5	10.0	168.8	
	20.0	10.0	159.1	1.73
	50.0	10.0	156.3	
	2.5	20.0	163.0	
	20.0	20.0	158.0	
	2.5	30.0	163.5	
	20.0	30.0	159.0	
	50.0	30.0	158.3	

Table 4 (con't)

Material	Load (kg.)	Time (sec.)	Vickers pyramid hardness no.	Standard deviation (VPN)
(Brass con't)				
180-H	2.5	10.0	224.0	
	20.0	10.0	222.0	3.74
	50.0	10.0	222.5	
	2.5	20.0	224.8	
	20.0	20.0	216.8	
	2.5	30.0	227.5	
	20.0	30.0	223.2	
	50.0	30.0	221.5	
Copper				
Commercially pure	2.5	10.0	90.0	
	10.0	10.0	72.3	1.16
	20.0	10.0	63.2	
	2.5	20.0	91.2	
	20.0	20.0	64.5	
	2.5	30.0	86.8	
	10.0	30.0	66.7	
	20.0	30.0	63.0	
159-S	2.5	10.0	112.5	
	20.0	10.0	113.9	0.944
	50.0	10.0	114.5	
	2.5	20.0	112.5	
	20.0	20.0	113.0	
	2.5	30.0	107.8	
	20.0	30.0	113.5	
	50.0	30.0	116.5	

Table 4 (con't)

Material	Load (kg.)	Time (sec.)	Vickers pyramid hardness no.	Standard deviation (VPN)
(Copper con't)				
Type unknown	2.5	10.0	104.3	
	20.0	10.0	106.5	0.724
	50.0	10.0	106.5	
	2.5	20.0	104.0	
	20.0	20.0	106.3	
	2.5	30.0	103.5	
	20.0	30.0	105.5	
	50.0	30.0	105.5	
Magnesium				
Commercially pure	2.5	10.0	37.9	
	5.0	10.0	33.0	3.10
	10.0	10.0	32.2	
	2.5	20.0	34.5	
	10.0	20.0	30.9	
	2.5	30.0	34.5	
	5.0	30.0	32.8	
	10.0	30.0	31.3	
Steel				
Armco	2.5	10.0	154.0	
	20.0	10.0	134.8	1.83
	50.0	10.0	133.0	
	2.5	20.0	147.0	
	20.0	20.0	135.0	
	2.5	30.0	141.5	
	20.0	30.0	135.0	
	50.0	30.0	128.0	

Table 4 (con't)

Material	Load (kg.)	Time (sec.)	Vickers pyramid hardness no.	Standard deviation (VPN)
(Steel con't)				
1020	2.5	10.0	194.5	
	20.0	10.0	188.9	3.22
	50.0	10.0	188.0	
	2.5	20.0	195.5	
	20.0	20.0	192.3	
	2.5	30.0	190.3	
	20.0	30.0	188.0	
	50.0	30.0	188.5	
1045	2.5	10.0	211.3	
	10.0	10.0	202.5	
	20.0	10.0	197.9	2.47
	50.0	10.0	195.0	
	2.5	20.0	208.3	
	10.0	20.0	200.0	
	20.0	20.0	195.5	
	2.5	30.0	203.0	
	10.0	30.0	197.5	
	20.0	30.0	195.5	
	50.0	30.0	195.3	
1095	2.5	10.0	344.0	
	20.0	10.0	324.2	5.13
	50.0	10.0	317.8	
	2.5	20.0	330.0	
	20.0	20.0	320.5	
	2.5	30.0	332.8	
	20.0	30.0	320.5	
	50.0	30.0	324.0	

Table 4 (con't)

Material	Load (kg.)	Time (sec.)	Vickers pyramid hardness no.	Standard deviation (VPN)
(Steel con't) 1.3% Carbon	2.5	10.0	250.5	
	20.0	10.0	234.0	6.20
	50.0	10.0	224.3	
	2.5	20.0	252.5	
	20.0	20.0	227.0	
	2.5	30.0	258.6	
	20.0	30.0	228.0	
	50.0	30.0	224.5	
Tantalum Commercially pure	2.5	10.0	141.0	
	20.0	10.0	138.3	2.23
	50.0	10.0	135.5	
	2.5	20.0	139.5	
	20.0	20.0	136.8	
	2.5	30.0	146.0	
	20.0	30.0	136.3	
	50.0	30.0	141.0	
Tin Commercially pure	1.0	10.0	6.9	0.167
	2.5	10.0	6.5	
	1.0	20.0	6.0	
	2.5	20.0	6.0	
	1.0	30.0	5.8	
	2.5	30.0	5.9	

Table 4 (con't)

Material	Load (kg.)	Time (sec.)	Vickers pyramid hardness no.	Standard deviation (VPN)
Zinc				
Commercially pure	2.5	10.0	49.4	
	10.0	10.0	47.2	1.01
	20.0	10.0	45.1	
	2.5	20.0	46.5	
	20.0	20.0	42.7	
	2.5	30.0	44.3	
	10.0	30.0	42.1	
	20.0	30.0	41.4	
Zamak 3	2.5	10.0	87.7	
	10.0	10.0	80.4	2.53
	20.0	10.0	76.0	
	2.5	20.0	82.6	
	20.0	20.0	72.5	
	2.5	30.0	78.9	
	10.0	30.0	73.9	
	20.0	30.0	72.1	
Zamak 5	2.5	10.0	103.5	
	10.0	10.0	94.0	0.970
	20.0	10.0	93.4	
	2.5	20.0	97.2	
	20.0	20.0	89.3	
	2.5	30.0	97.4	
	10.0	30.0	89.9	
	20.0	30.0	89.2	

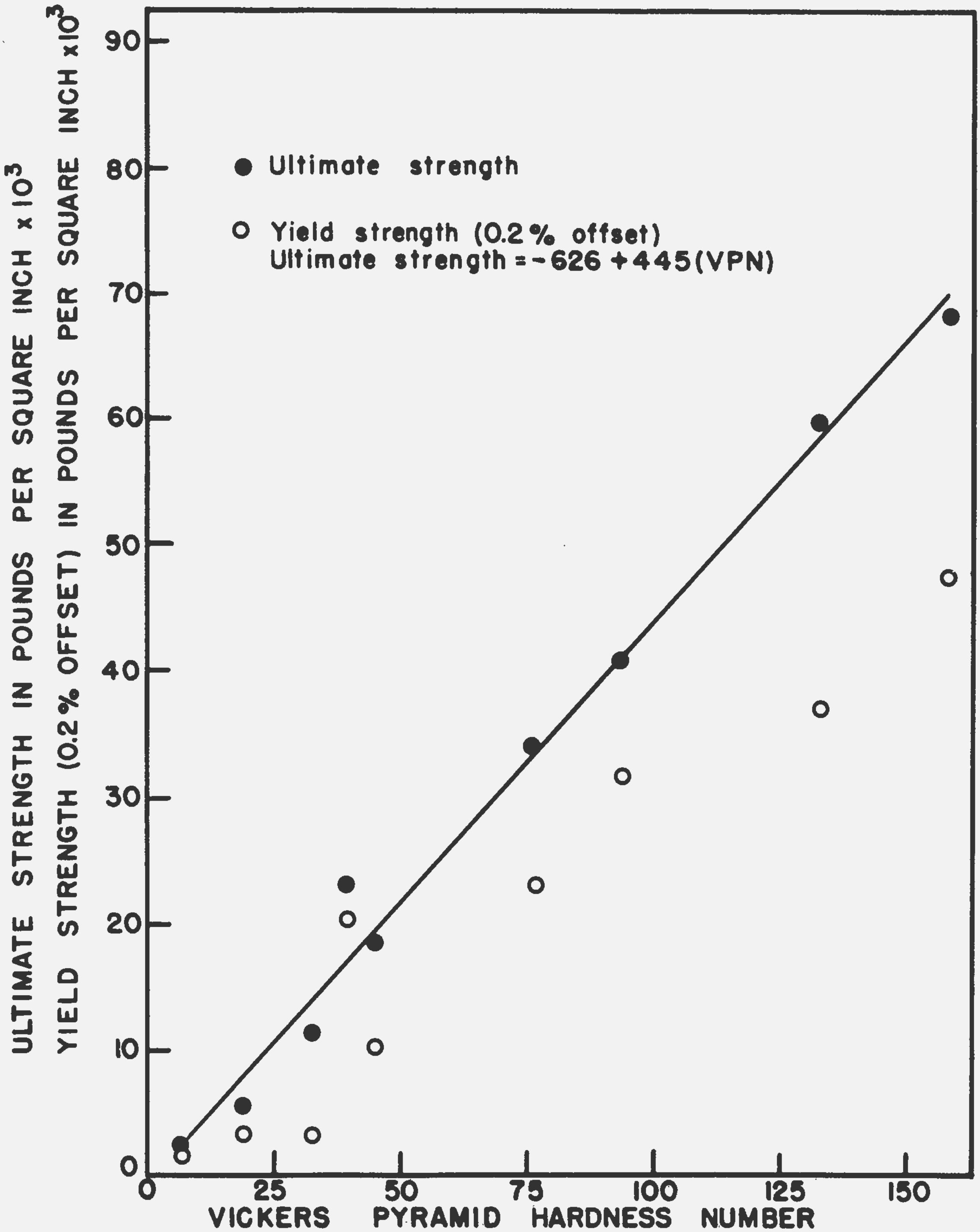

FIG. 2 STRENGTH VS HARDNESS NUMBER FOR MATERIALS WITH A MODULUS OF ELASTICITY OF APPROXIMATELY 10,000,000 PSI.

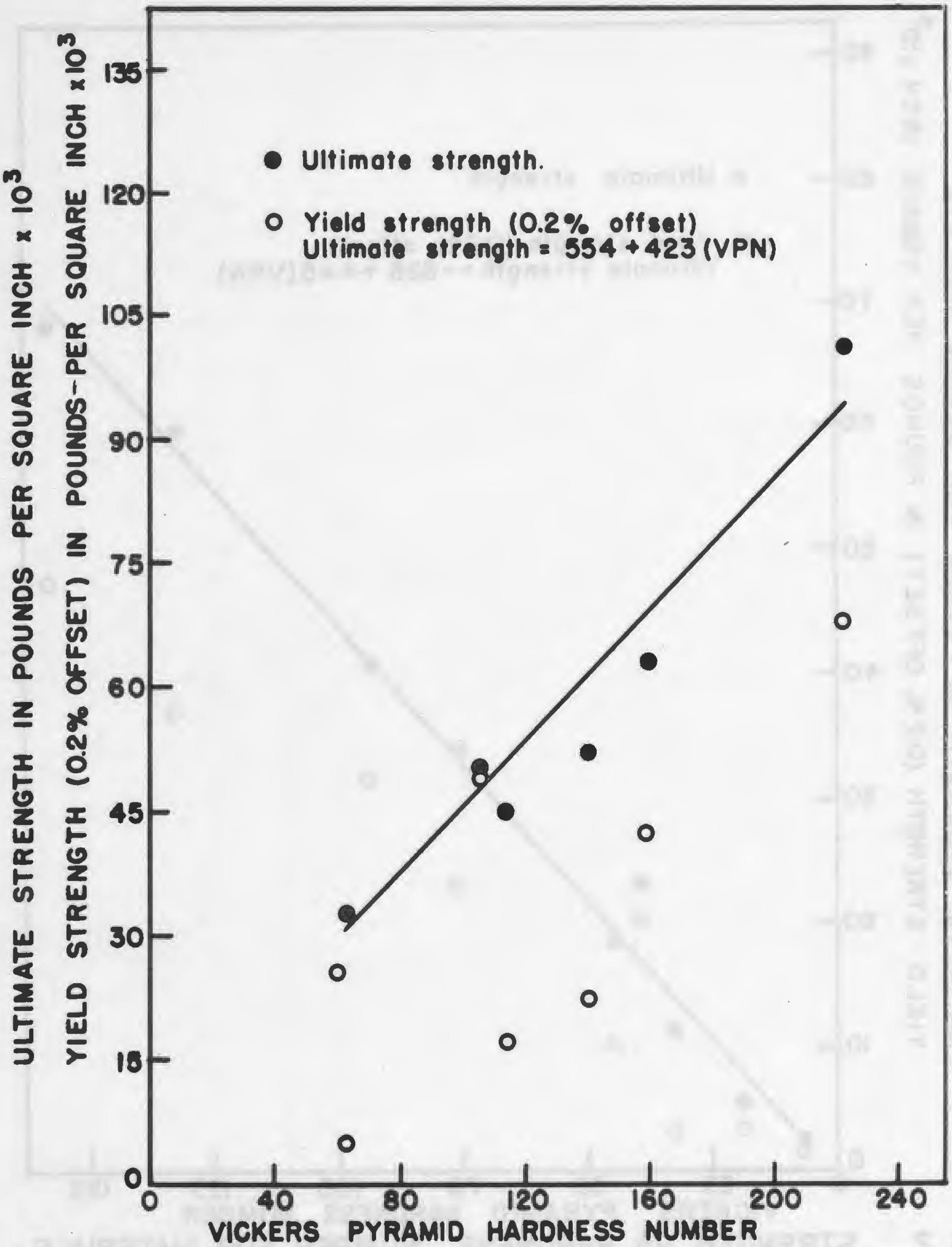

FIG. 3. STRENGTH VS. HARDNESS NUMBER FOR MATERIALS WITH A MODULUS OF ELASTICITY OF APPROXIMATELY 17,000,000 PSI.

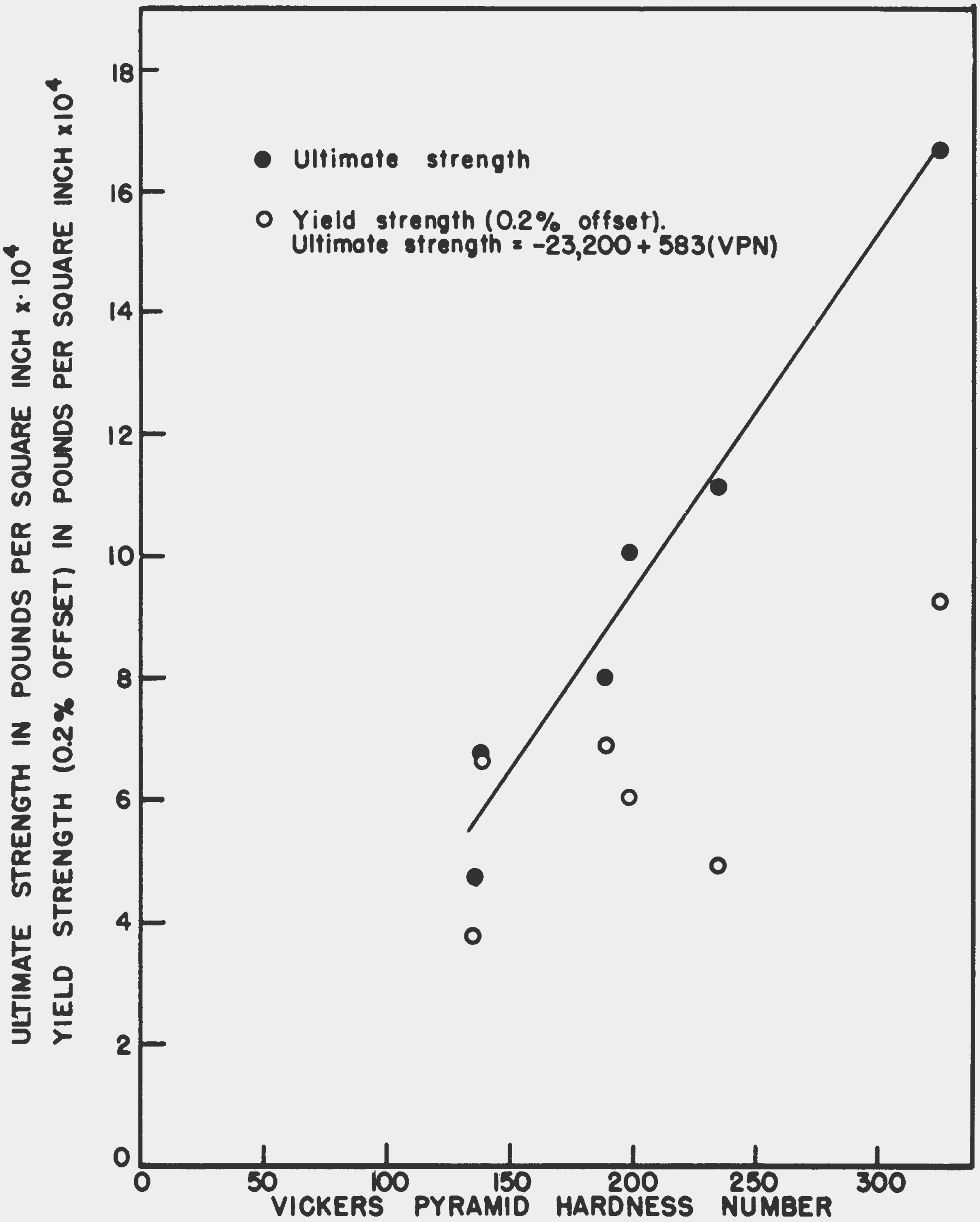

FIG. 4 STRENGTH VS. HARDNESS NUMBER FOR MATERIALS WITH A MODULUS OF ELASTICITY OF APPROXIMATELY 30,000,000 PSI.

2. Ultimate strength = 554 + 423(VPN) for materials with a modulus of elasticity approximately equal to 17,000,000 psi.
3. Ultimate strength =-23,200 + 585(VPN) for materials with a modulus of elasticity approximately equal to 30,000,000 psi.

In these equations the ultimate strength is in pounds per square inch and VPN is the Vickers pyramid hardness number. The slopes of the lines and the intercepts of the lines on the axes as given by the equations do not increase with an increase in the modulus of elasticity. The equation for metals with a modulus of elasticity of about 10,000,000 psi. agrees with data determined by the author for thorium, within the limitations of both sets of data. No published data or equation could be found for metals with a modulus of elasticity of about 17,000,000 psi. for comparison with the determined equation. The equation for metals with a modulus of elasticity of about 30,000,000 psi. agrees, within the accuracy of the data used to determine the equation, with data published for steels by Williams (20, p. 463).

In Figure 5 is shown a plot of Vickers hardness number versus the test load for the three testing times for the 1045 steel hardness specimen. The hardness data for the other specimens would show similar curves if plotted as in Figure 5. Because the Vickers hardness number is dependent upon the applied load and time of testing the author suggests that in reporting Vickers hardness numbers both the load and testing time be stated.

The equations listed are limited in accuracy by the small number of points used to determine each equation, by the accuracy of the tensile test data, and by the accuracy of the hardness test data. The tensile test data would have been more accurate if more than one test had been made on each material and an average of the tests reported. The homogeneity of the tensile and hardness test specimen has a large effect on the data obtained in the test. The standard deviation of ten hardness tests for each metal was found for an indication of the homogeneity of each metal and they are tabulated in Table 4. It is apparant that the standard deviations differ considerably in magnitude and hence the metals differ substantially in homogeneity.

V. SUGGESTIONS FOR FURTHER STUDY

There are many avenues for research in the hardness field. Practically nothing of an analytical nature has been done. An analysis of the indentations caused by variously shaped indenters would be most helpful for the construction of conversion charts of hardness to hardness, and hardness to strength. Perhaps an approach

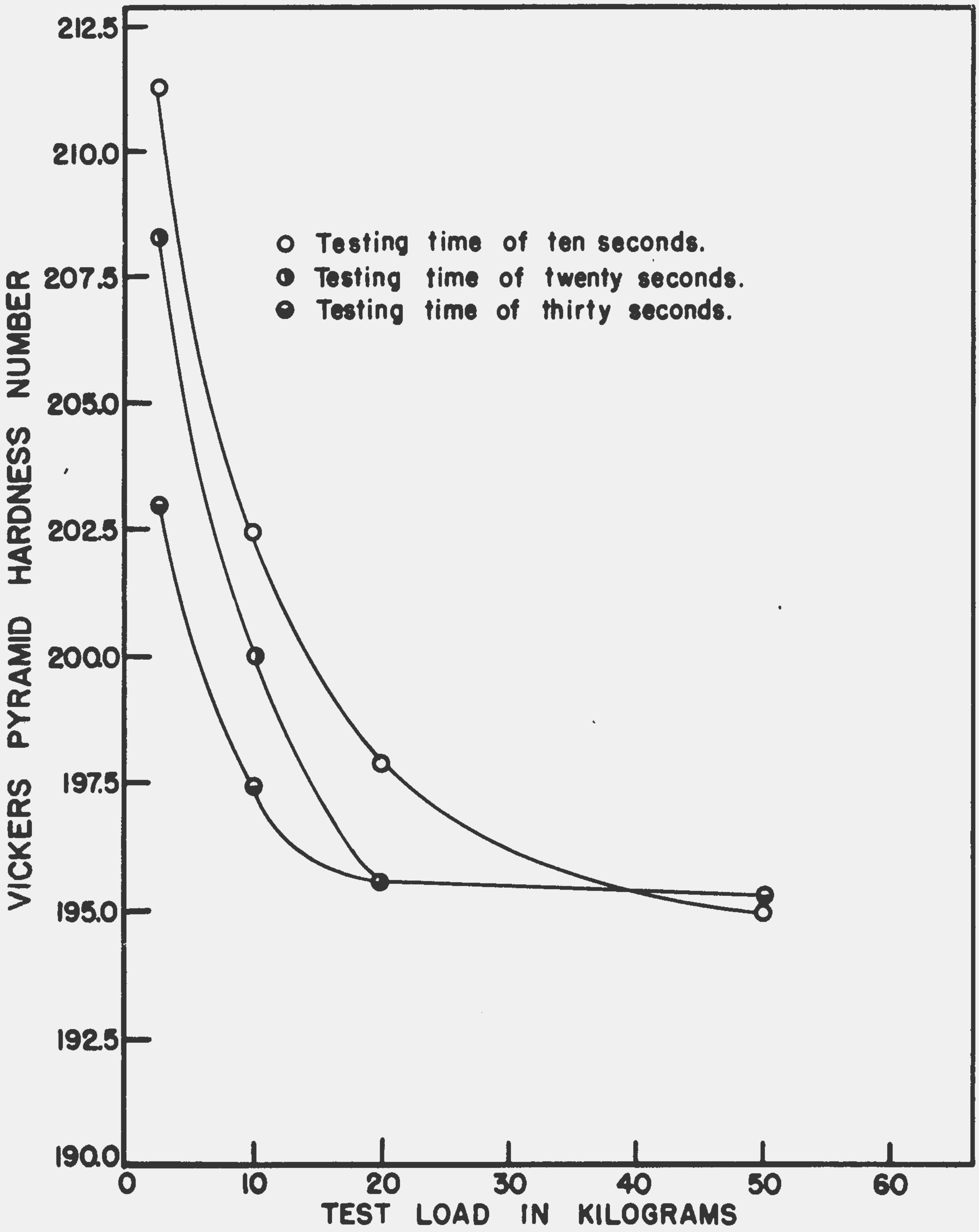

FIG. 5 VICKERS PYRAMID HARDNESS NUMBER VS. TEST LOAD IN KILOGRAMS FOR DIFFERENT TESTING TIMES IN SECONDS FOR THE 1045 STEEL.

using the photoelastic method would be helpful to the solution of the hardness problem. The effect of time of testing on the hardness number, for variously shaped indenters, needs more investigation, particularly for long time intervals of testing.

Very little work has been done ~~on~~ an analysis of the dynamic hardness test and it offers many problems to be solved.

VI. SUMMARY AND CONCLUSIONS

The object of this investigation was to determine whether or not a relationship existed between the yield strength, modulus of elasticity, and the Vickers hardness number for various metals. Tests were also performed to determine whether or not the Vickers hardness number was independent of the time interval and applied load used in testing.

Equations were derived for determining the ultimate strength of a metal from its Vickers hardness number for three modulus of elasticity ranges.

Within the limits of this investigation the following conclusions seem reasonable to the author:

1. There is no discernible relationship between the yield strength and the Vickers hardness number.
2. There is a linear relationship between the ultimate strength and the Vickers hardness number for materials with approximately the same modulus of elasticity. The relationship can be used for predicting the ultimate strength of a metal from the knowledge of its Vickers hardness number.
3. The Vickers hardness number is dependent on the length of time of the testing cycle and the magnitude of the applied load.

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