Indentation HARDNESS TESTING

by

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To HELEN

Preface

For over twenty years the author has been engaged in work relating to hardness testing. During this period thousands of inquiries have come to his attention through correspondence, personal conferences, committee work of the American Society for Testing Materials, lectures and educational work with members of the American Society for Metals and the American Society for Tool Engineers. Such inquiries requested information relating to all phases of hardness testing and were solicited by engineers, metallurgists, inspectors and individuals making use of hardness tests in routine testing and establishing hardness specifications.

This work, together with the knowledge acquired by the author through association with others interested in hardness testing, is being presented in this book. Sufficient information is given to acquaint the user of hardness testing equipment with the usual problems with which he must cope.

No attempt has been made to consider hardness in detail from the theoretical standpoint, nor is this a complete historical study of the development of the hardness test. Rather, an endeavor has been made to describe the hardness testers in common use in the United States and discuss in detail the problems associated with the use of hardness testing equipment.

Sufficient historical background is presented to acquaint the reader with the development of various instruments. Likewise, sufficient theoretical consideration is given so that the reader may acquire a thorough knowledge of the present status of hardness testing.

Three special problems continually arise in hardness testing, namely, testing thin materials, conversion from one hardness scale to another, and testing cylindrical parts. Each of these is discussed in a separate chapter.

A number of metallurgical and testing engineers kindly consented to review sections of this book pertaining to work with which each was familiar. The author expresses his gratitude to these men for their help and suggestions. It was hoped that by such aid the technical facts would be verified, and personal preferences of the author eliminated. This group includes the following, who are well-known for their work in the field of hardness testing: Ladsivar Boor, T. H. Gray, R. H. Heyer, R. L. Kenyon, Howard Scott, W. Shore, W. A. Stadtler, Douglas Tate, David Wallace and B. L. Wilson.

Particular gratitude is expressed to Chas. H. Wilson, founder and former president of the Wilson Mechanical Instrument Co., Inc., for his help and encouragement. Mr. Wilson wrote the Foreword and reviewed the chapters on Rockwell testers. Inasmuch as there is nowhere a published record of the development of the Rockwell tester, and in view of the importance of this test in the metallurgical world, considerable effort has been made to present a clear and concise resume of this work.

The cooperation of various manufacturers of hardness testing equipment in supplying details and photographs of the various apparatus that they manufacture is acknowledged and appreciated. The technical staff of the Wilson Mechanical Instrument Co. has also been most helpful.

The author expresses his appreciation to George Herman for his work in preparing the drawings used in this publication.

It is hoped that this book will enable those interested in hardness testing to acquire a much clearer understanding of the subject and that it will inspire many to explore further this useful and fascinating subject.

Foreword

You may write your own definition of hardness: neither statute law nor the laws of physics define it, nor are they ever likely to, though usage and convenience have suggested and brought about an accepted general meaning of the term, which has been used in the field of metallurgy, and in kindred arts and crafts. This meaning is that resistance to indentation of a given material, compared to such resistance offered by other materials, is an index of hardness. This limited meaning is condensed into the accepted phrase "indentation hardness"; where the word "hardness" alone is used in metallurgy, the modifying word "indentation" is generally implied.

While concerning myself exclusively for over a quarter of a century (but not now) with the design and manufacture of hardness testers, I acquired an ever-increasing respect for archaeology. The archaeologist uncovers fragments of human and animal bones and a few remains of tools, weapons and, perhaps, utensils of some prehistoric beginnings of civilization and constructs therefrom a conception, and perhaps a model, of the life that accounted for them.

In making an indentation hardness test of any material, be aware that the indenter forced into that material comes to rest when its indenting load is exactly supported by whatever it is that resists further indentation. Now the only absolutely certain thing about what does resist further indentation is that the material we set out to test does not of and by itself do that job. It is the cold-worked, over-strained and crushed remains of that material, housed in a frame or cup of strained, but not crushed, portion of the original material, that does the supporting, and that is what we accept as our index of the hardness of the original material. And the astonishing thing is that the index of hardness so obtained (by fixed load and dimensional measurement of the impression, or by fixed dimension of the impression and measurement of requisite load) is so useful a value. It is useful, and is quite usually accepted and very generally employed. The un-cold-worked hardness of the original material is not discovered by any indentation hardness test. Perhaps for most purposes it would be of no use to know it, for it is difficult to conceive of many practical uses to which any material could be put where the simon-pure hardness of the original material would be a sure index of any useful property. That explains my archaeological analogy.

Probably the most important reason for what has been mentioned above is that therein lies the key to understanding why there is not, and cannot be, any simple mathematical relation between indentation hardness values obtained with different loads and different shapes of indenters, for all such differences result in different degrees of cold-working of the material being tested.

Unlike other physical conditions, such as temperature, pressure, electrical resistance, etc., hardness has no basic reference standard. For convenience of checking individual instruments in service something is needed for reference, and that something must check the complete equipment as a unit that will, for example, comprise the machine in its load application, the indenter, and whatever system of measurement of indentation is employed.

Whatever piece of metal may be used for the purpose (test block is the usual term for it) necessarily falls far short of the ideal for two important reasons. First, it must have a serviceable area; yet it is practically impossible to produce absolute uniformity in hardness over an area, and equally impossible to determine the uniformity without such a multiplicity of indentations that no part of the surface is left available for checking purposes. Furthermore, any piece of metal varies in hardness with temperature change; what is still worse, there is continual, though sometimes small, change in hardness with time, for in its preparation the metal has had to go through some sort of mechanical or heat treatment, or both. The second difficulty in preparing a piece of metal for use as a service standard is lack of any basic reference standard by which to know its hardness.

It is an expensive and tedious procedure to sail with reasonable exactness through these fogs, yet it has been done for many years without getting lost. I mention it because those who do not comprehend the difficulties and natural limitations tend to believe that the true north of hardness standardization is clear, certain and self-evident.

The need to make indentation hardness tests on extremely shallow surfaces or within minute areas has recently been manifested in so many laboratories that microhardness testing equipment has had to be developed to meet that need. The National Bureau of Standards has done important work in that direction and has inspired the development of equipment that is answering many requirements. In this field another difficulty is encountered, due to the diminutive size of indenters and indentations, and the errors still inherent in optical measurements of such small dimensional values. Those employing such microhardness equipment must realize that careful technique in operating the equipment and genuinely scientific direction of the work and interpretation of results are imperative when new investigations are afoot, for there is no game of "blind-man's buff" about it.

Mr. Lysaght has had the experience, over a score of years, of making thousands of hardness tests with different instruments and on an enormous variety of different materials. He has for many years attended the sessions of Committees on Hardness Testing of the leading technical societies, has visited hundreds of plants to investigate difficulties in and disagreements in hardness tests, and has given many lectures on hardness testing to practical men in the metallurgical field, during which he has been bombarded with questions. He has learned as much as he has taught about practical applications of hardness testing. I doubt if there is anyone better able to give advice on such testing, and I am glad to see his experience culminate in this book, for while he is no theoretical physicist and makes no claim to being an authority (whatever that may be) on hardness testing, his opinions have been requested and respected by many experts.

CHARLES H. WILSON

Founder and former President of the
Wilson Mechanical Instrument Co., Inc.

Contents

Chapter I

Hardness Concepts

Hardness as applied to metals has been the subject of much discussion among physicists, metallurgists and engineers, and it has been given many technical and popular definitions. These range from that of Dr. L. B. Tuckerman of the National Bureau of Standards, in which he represents hardness as "a hazily conceived conglomeration or aggregate of properties of a material more or less related to each other," to the commonly accepted idea of hardness by the metal-working industry as "resistance to permanent indentation."

Dr. Tuckerman elaborates on his description and includes in the scope of hardness properties such varied attributes as resistance to abrasives, resistance to scratching, resistance to cutting, ability to cut other materials, resistance to plastic deformation, high modulus of elasticity, high yield point, high strength, absence of elastic damping, brittleness, lack of ductility and malleability, high melting temperatures, magnetic retentivity, etc. Reference to Dr. Tuckerman's definition is not intended to induce confusion, but rather to show the complex nature of hardness, and to point out that hardness results from numerous properties which may vary independently of one another. This accounts for the lack of a definitive meaning of the term "hardness" and for the many widespread definitions and methods of testing it.

Before considering indentation hardness and the instruments used to measure permanent indentation resistance, reference should be made to such other concepts of hardness as resistance to scratching, wear or abrasion, and cutting, mentioned above. Conceptions of hardness as related to or determined by magnetism or electrical characteristics will not be considered. This does not mean that such a relationship does not exist, but rather that the application is so specialized that it holds little interest for the engineer interested in controlling hardness. The physicist, on the other hand, may find such relationships of greater interest than indentation hardness.

Some detailed description of methods used to determine hardness of minerals by scratching is included because scratch hardness testing, as considered here, consists of penetration of the surface of the material being tested by a testing point and the removal of material when the test point moves over the surface under a testing load. The scratch is produced by flow under load, and in this respect it bears some resemblance to the indentation hardness test. When the material is torn away and no plastic flow results, the test is considered as abrasive hardness and will be discussed only briefly.

Scratch Hardness

Excepting the file test for the time being, the earliest form of scratch hardness goes back to Réaumur in 1722. His scale of testing metals consisted of scratching a bar, which increased in hardness from one end to another. The hardness was indicated by the position on the bar which the metal being tested would scratch.

In 1822 the Mohs scale of hardness for minerals was introduced, and it is still used as a classification of minerals. It simply consists of 10 minerals arranged in order from 1 to 10. Diamond is rated as the hardest and is indexed as 10; talc as the softest with index number 1. Each mineral in the scale will scratch all those below it as follows:

Diamond	10	Apatite	5
Corundum	9	Fluorite	4
Topaz	8	Calcite	3
Quartz	7	Gypsum	2
Orthoclase (Feldspar)	6	Talc	1

The steps are not of equal value and the difference in hardness between 9 and 10 is much greater than between 1 and 2. To determine the hardness of a mineral it is merely necessary to determine which of the standard materials the unknown will scratch; the hardness will lie between two points on the scale—the point between the mineral which may be scratched and the next one harder. This is a simple test which has served mineralogists well, especially in field tests. It is not exactly quantitative and the standards are purely arbitrary numbers.

The materials engineer and metallurgist find little use for the Mohs scale; but to cite a few examples of the hardness of common metals in the Mohs scale, "Armco" iron is between 3 and 4 and copper between 2 and 3. Hardened tool steel is between 7 and 8.

At least two instruments have been designed in the United States for quantitatively measuring hardness by the scratch method. The earlier and less familiar one was designed by Prof. L. C. Graton of Harvard. One instrument, built at the Geophysical Laboratory, was intended to overcome the disadvantages of the Mohs scale in that the measurements would eliminate the personal judgment factor, and the overlapping of the hardness ranges of various minerals greatly reduced.

The instrument consisted primarily of a microscope, stage, sliding weight to apply loads to 3 grams, and a diamond point. The diamond was ground to a semi-circular blade-like edge with a 45° included angle. In operation, the mineral being tested is scratched by the diamond and the scratch is compared with standard limit scratches in the microscope eyepiece disc. The load is adjusted and additional scratches made until a scratch is produced within the standard limits. Usually this is accomplished in three trials. The scale is based on the actual weight on the testing point in grams.

The system has two advantages. (1) It is simple; no micrometer eyepiece for measuring the width of the scratch is necessary. (2) Shallow scratches only are produced, thus preserving the highly polished surface of work, which would not be the case if deep scratches were made, especially in soft materials. It was recommended for a quick and easy method of determining the relative hardness of ore minerals within limits necessary for identification only. By standardizing on the microscope equipment, width of scratch and diamond point, satisfactory results are obtained for this purpose.

The best known scratch-hardness tester is the Spencer Bierbaum microcharacter (Fig. 1). Designed by C. H. Bierbaum, it consists of a diamond mounted at the end of a tapered steel spring. The other end of the spring is fastened to a balanced arm which holds a 3-gram standard weight. The surface of the material to be tested is moved under the diamond point at a fixed pressure. The width of the cut is measured under a microscope and the hardness determined from a formula.

Several unique features are incorporated in the design of this instrument. The specimen, which is highly polished and usually lightly etched, is clamped on a mechanical stage similar to that found on metallurgical microscopes. The sample is drawn under the diamond by a mechanical feed ordinarily actuated by a hand-driven worm and wheel. During the scratching operation, the diamond point is lubricated by a superfine watch oil.

After the scratching operation the sample is cleaned to remove the oil, and the width of the scratch is read in microns (1 micron = 0.001 mm) by means of a filar micrometer eyepiece. Magnifications of from 500 to 4400 diameters are used; for most readings oil-immersion objective lenses are used. The microscope equipment must be of the highest accuracy.

The scale is derived by using the reciprocal of the cut width in microns squared multiplied by 10,000. By formula:

$$K = \frac{10{,}000}{W^2}$$

K = microcharacter scale
W = width of cut in microns

The diamond is the shape of a solid right angle or the corner of a cube. One corner makes up the cutting edge. The angle of scratching is calculated to be 35.25°. The diamond must be ground to extreme precision.

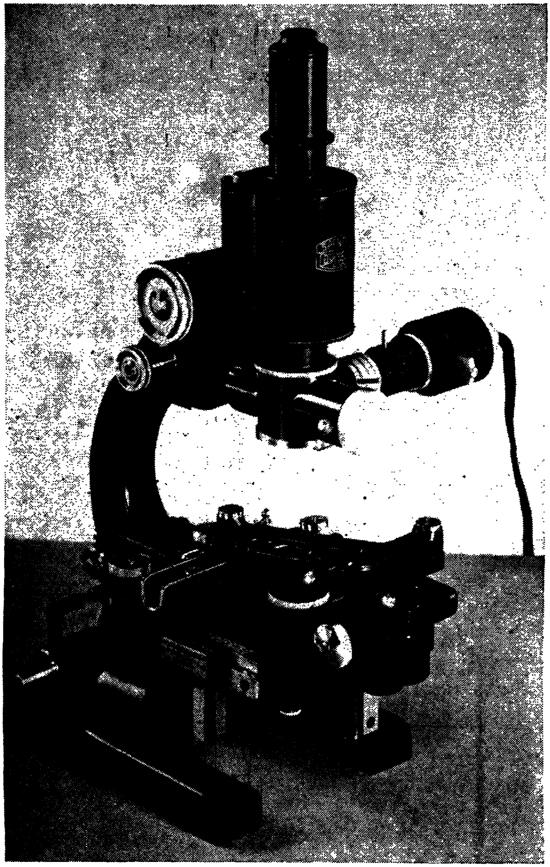


Figure 1. The Spencer Bierbaum microcharacter.

(Courtesy American Optical Co., Buffalo, N. Y.)

The point must be sharp at high magnification and the facets true plane surfaces; their intersections must be sharp straight lines at right angles.

The microcharacter has been explained in some detail, as reference will be made to it later in connection with microhardness testing and the testing of non-metallic materials.

Abrasive and Cutting Hardness

Abrasive hardness may be defined as resistance to wearing away. Resistance to wear or abrasion is generally thought of as the amount of material removed under certain conditions. Abrasion of metals has been the subject of many investigations during the past several years, but as yet no one method or group of methods has been evolved which can be recommended for studying wear resistance. Abrasion between two metals will vary with the coefficient of friction between surfaces, surface conditions, speed of test, cold working and other factors. Many investigators have developed a wear tester which gives them important and valuable results insofar as their one particular problem is concerned; but little has been accomplished in adapting the test to different substances on a universal basis.

Cutting hardness is an indication of the workability of metals. The workability or machinability of metals in a machine tool depends on many factors, such as toughness, abrasive qualities and hardness, as determined by resistance to permanent indentation. Several tests have been developed for determining cutting hardness but the most that can be said for them is that the results are comparable for different metals only within very narrow limits. The tests are generally made on a specially modified machine tool and the variables involved include sharpness of cutting tool, speed of test, and amount of pressure applied to the cutting tool.

Indentation Hardness

Having briefly discussed other concepts of hardness, let us now consider indentation hardness in detail. The metallurgist defines hardness as resistance to permanent deformation and shows how metals deform into the plastic stage after they have passed their elastic limit and acquire a permanent set. In measuring hardness, however, allowance must be made for friction between the metal being tested and the indenting tool; this accounts for the accepted definition of hardness as resistance to permanent indentation. Hereafter in this book this definition will be applied to the word "hardness," except when otherwise indicated. It includes the original resistance of the metal to permanent deformation plus the additional resistance due to severely working or strain-hardening the metal by the indenter during application of the testing load.

Long before 1700 philosophers and scientists discussed hardness, but these early investigators were content to speculate on its nature. As we noted earlier, Réaumur first measured hardness by the scratch method in 1722. More important, however, than his scratch test, is the fact that he was one of the earliest investigators of indentation tests. He studied a variety of tests; he used chisels as indenting tools, and then mutual indentation by applying pressure to triangular prisms of different materials (Fig. 2a). This latter work was developed more fully by Haigh (Fig. 2b) in 1920, who tested right-angled edges of test pieces of the same material; these were pressed into each other and the width of the indentation measured. The Haigh hardness number is P/l^2 when P is the load applied in kg and l the width of the indentation in mm. About 1897 Foeppl and Schwerd (Fig. 2c) suggested the use of cylindrical test bars of the same material with the longitudinal axes at right angles to each other. This hardness number is likewise expressed as P/l^2, but this time l is the width of the resulting saddle-shaped impression.

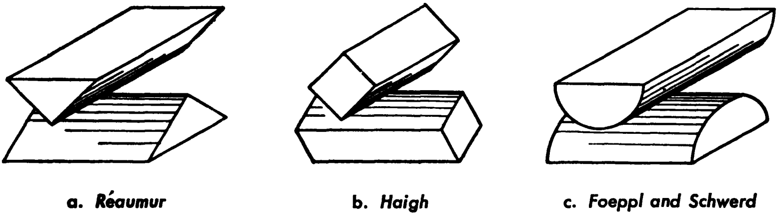

a. Réaumur b. Haigh c. Foeppl and Schwerd

Figure 2. Various forms of mutual indentation.

In 1859 Calvert and Johnson reported results obtained on a hardness tester in terms of the load required to produce an indentation of 3.5 mm. The depth of penetration was measured by a scale equipped with a vernier. The load required to penetrate the 3.5 mm was called the hardness. The penetrator was a truncated cone 7 mm long, 5 mm wide at the top and 1.25 mm wide at the point. Mostly soft metals were studied.

Such was the beginning of indentation hardness. Today the indentation hardness test is used in practically every metal-working plant as a means of checking the quality and uniformity of metals and metal parts. The test serves as a control or designation of the heat-treating or processing of the metal, or is used in estimating the tensile strength. Because of the simplicity of the indentation hardness test as carried out by modern hardness testers, and its relatively small cost, it is probably the most commonly employed test in industry.

The more commonly known hardness testers and their use and application will be described in detail. Each has its place. All indentation hardness tests for metals have one thing in common—and it is the crux of many problems, investigations, and research being studied in connection with hardness testing. This is the fact that the metal under test changes in hardness and becomes more resistant as penetration increases up to the point of rupture of the grain structure. Therefore, the hardness depends as much upon the degree to which the metal has previously been deformed, as it does upon the rate at which the deformation has been carried out. This varies with the metal. If anyone interested in hardness can appreciate that simple principle, he has gone a long way to having a clear understanding of the indentation test.

With the exception of the Scleroscope, only instruments measuring static hardness will be discussed. This is in line with the accepted definition of hardness. While it may be true that dynamic loads might permit hardness to be defined in terms of the fundamental units: length, mass, and time, it must also be admitted that users of such tests are at once confronted with the problem of deciding what form of energy should be considered in calculating the results. Is it the initial energy at the instant of contact or the energy absorbed in making the indentation? Most metallurgists and engineers agree with E. Meyer of the Material Testing Laboratory at the Imperial School of Technology (Charlottenberg, Germany) that dynamic effects should be eliminated from the conception of indentation hardness.

No attempt has been made to discuss all the early investigations of hardness. Invaluable contributions were made by Huyghens, Le Chatelier, Van Musscheribroeck, Seebeck, Franiz, Martens, Hertz and many others. Most of their work is described in detail by S. R. Williams in his excellent book, "Hardness and Hardness Measurements."

Likewise, no reference is made to the internal conditions which determine hardness properties, as this is a matter for the physicist or metallurgist. The physicists are perfecting this picture and with the use of the x-ray spectrograph are able to confirm that metals are crystalline aggregates. They are also studying the internal atomic structure of individual crystals and the way in which they deform along their planes of cleavage.

With the exception of the Brinell tester, most modern testers use diamond penetrators or indenters. Diamond is the hardest of all known materials. Its resistance to deformation during the application of the testing load is as high as possible; thus the test results obtained are affected to a minimum extent.

The shaping, selection, and mounting of diamonds is a skilled art. Diamonds free from breaks and cracks should be selected for use as penetrators. They must be mounted with a faultless and non-elastic support. The diamond point must be accurately cut or polished. In the case of cone-shaped penetrators with rounded apex, the point must be tangent to the cone on its whole periphery.

It should be remembered that all the accuracy of a well-built hardness tester is lost if poorly shaped penetrators are used.

It is impossible to predict the life of a diamond used as a penetrator. Generally speaking, the diamond point does not wear away, but rather becomes chipped, probably due to shock, poor support of specimen being tested, or fatigue. In most cases it is then unsuitable for further use, as regrinding may not be economical or satisfactory.

Diamonds should be examined after being shaped under high magnification. They should then be checked on test blocks, which have been carefully calibrated.

All hardness-testing equipment should be kept clean and free from dirt, grit and especially dust from grinding equipment.

The instrument should be mounted on a sturdy bench in a location which is free from vibration and especially from severe shock, such as caused by punch presses. If vibration or shock is present it should be eliminated by special mounting.

The oiling and maintenance instructions of the manufacturer should be carefully followed.

This is a good place to emphasize that many times it is necessary to prepare a smooth surface for accurate evaluation of hardness, regardless of which test is made. The degree of finish will depend on the depth of indentation and a better finish is required as the impressions become more shallow. The use of a minor load or preload to some extent lessens the requirement of a good surface finish.

As each method of test is discussed, the matter of surface finish will also be considered, but it must be remembered that preparing the surface may introduce the effects of surface work-hardening by machining and polishing on metals which are susceptible to work-hardening. Therefore, the selection of a hardness test which requires little surface preparation is advantageous.

F. C. Hull and H. R. Welton[1] have made a study of work-hardened surfaces of fatigue specimens which convincingly demonstrates the effects of surface work-hardening. It applies to specimens for hardness testing as well as to fatigue specimens.

Light grinding carefully executed, followed by rubbing on No. 00 emery paper, probably represents the best method of surface preparation to keep cold-working at a minimum. Generally speaking, grinding causes less superficial hardening than filing or machining. In some cases, however, filing has no great effect.

When preparing heat-treated samples by grinding, care must be taken not to grind so severely as to cause any local tempering or burning of the piece.

Reference

1. Hull, F. C., and Welton, H. R., "Work Hardened Surfaces of Fatigue Specimens", *Metal Progress* (December, 1945).

Chapter II

The Brinell Test

The beginning of the twentieth century marked a milestone in the history of hardness testing. In 1900, Dr. J. A. Brinell, Chief Engineer at Fagersta Iron Works in Sweden, presented a paper to the Swedish Society of Technologists, in which he described his ball test. In the same year he showed his hardness tester at the Paris Exposition. His method was destined to become the most important test for the metal worker throughout the next twenty years, and to share in importance with later developments.

The Brinell method consists of indenting the metal with a 10-mm diameter steel ball subjected to a load of 3,000 kg. For soft metals, the load is reduced to 500 kg, to avoid too deep an indentation. The load is applied for 30 seconds, after which it is removed; the diameter of the recovered indentation is measured and the Brinell hardness number calculated by dividing the load applied by the surface area of the indentation, or by the formula:

$$\text{Brinell hardness number} = \frac{L}{\frac{\pi D}{2}\left(D - \sqrt{D^2 - d^2}\right.}$$

L = load in kilograms
D = diameter of ball in millimeters
d = diameter of indentation in millimeters

The diameter of the impression should be the average of two readings at right angles. The table on page 244 gives the corresponding hardness number for each diameter of ball impression.

This test is classified as a static type *i.e.*, the stressing force producing the indentation is applied slowly, in contrast to the dynamic test when the indentation is produced rapidly as by a falling mass.

The load is removed before reading the indentation diameter, thus allowing the specimen to recover. This is desirable from a measurement standpoint as it greatly simplifies the problem of indentation diameter determination.

The Brinell number of a material, as defined above, is the ratio L/A, where A is the surface area of the indentation in square millimeters. This ratio is constant for a given material only when the applied load is always the same and the diameter of the ball is always the same. Brinell realized this and was well aware of the fact that the hardness number varied with the applied load. He even suggested testing with a constant-*diameter impression and using a varying load as a measure of hardness. As this would involve many problems of a practical nature, Brinell* recommended a constant load and a variable-size impression. Much has been written and will be discussed later with reference to L/A being constant for a given material, provided that penetrators are geometrically similar and that loads are proportional to the square of the linear dimensions of the penetrator.

Though aware of all these anomalies, Brinell introduced his test as a simple and accurate means of measuring indentation hardness, and the widespread use of the Brinell number after nearly 50 years is proof of its value. A single number, which could be duplicated when load and penetrator were within prescribed limits of accuracy was what Brinell gave to the metal-working industry—3,000 kg for hard metals and 500 kg for soft metals as the load, and a 10-millimeter diameter steel ball as the penetrator.

For two observers using different equipment at different locations to arrive at the same result, it is necessary to control closely all the factors involved in the Brinell test. These include the apparatus, the shape and material of the ball, the measuring device, and the test specimen. Each of these will be considered in detail.

The Apparatus

Various kinds of machines are available for making the Brinell test, the most common of which is the hydraulic type. One of these is shown in Fig. 3. It consists of a ball mounted in a plunger and attached to a piston working in a main cylinder with so perfect a fit that no packing is necessary. A crossbar and weights are attached to the top of a second piston in a small cylinder connected directly with the main cylinder, and the load applied is determined by weights acting on the smaller piston, of such value as to apply the proper load to the penetrator. Oil is forced into the main cylinder by a hand pump; the weights are lifted when the proper pressure is built up. Thus the built-up pressure maintains the load constant as long as the piston floats. A pressure gauge indicates the approximate load. The pressure is released by opening a valve. The specimen is placed on an anvil and is brought into contact with the ball by means of an elevating screw and handwheel.

Other methods of applying the load involve combinations of weights and levers or a gear-driven screw. These are designed in various ways; each has its own characteristics and it would be an arduous task to describe them all. Often the Brinell test is made in a small universal testing machine, but by far the majority of Brinell tests are made on a hydraulic-type machine. The important requirement is that the load *applied be as nearly correct as possible, and in this respect considerable latitude is noticed when different specifications are examined*

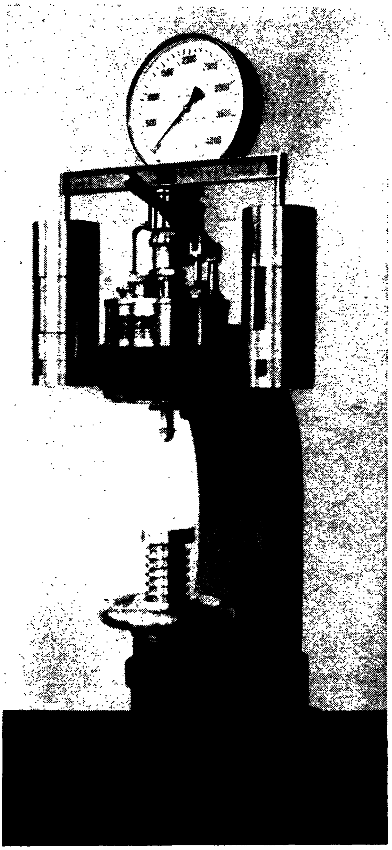


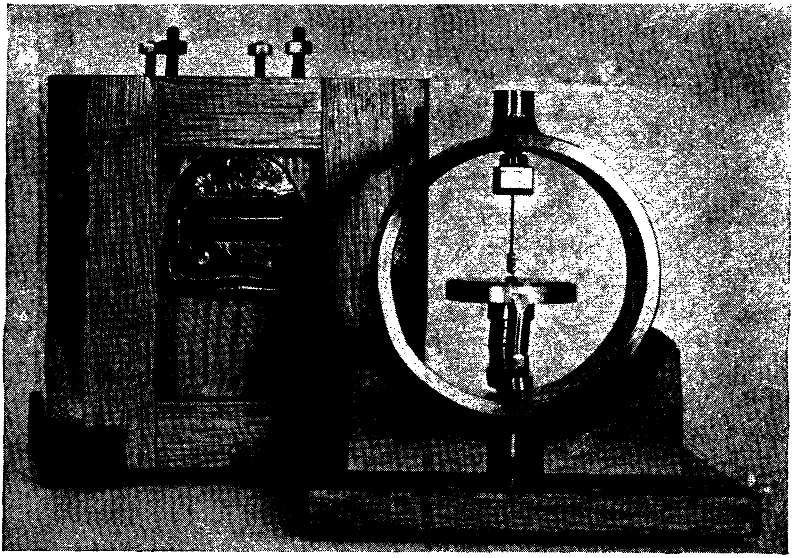
Figure 3. The Alpha Brinell tester.

(Courtesy Herman A. Holz, New York, N. Y.)

The American Society for Testing Materials designation E 10–27, covering Standard Method of Test for Brinell Hardness of Metallic Materials, states that a Brinell machine is acceptable for use over a loading range within which its load-measuring device is correct to 3 per cent. The British Standard Institution # 240 Part 1 (1937) for British Standard Method and Tables for Brinell Hardness Testing specifies that the accuracy of the testing machine shall be within ½ per cent of the load applied to the test-piece. The National Bureau of Standards Research Paper RP 903 recommends that the error in the load applied by the machine should not exceed ⅓ per cent. Material having a Brinell number of 300 would show an error of about three numbers with a 1 per cent error in load.

Precision equipment may now be built in modern instrument shops to very close tolerances, and good practice would require that the applied load be accurate to at least ½ per cent. This would keep the error in the Brinell number from that source to approximately the same magnitude.

The load should be checked by periodic calibration, preferably with a proving ring (Fig. 4), though weights and levers may be used. The proving ring is an elastic calibration device, which is placed on the anvil of the tester; the deflection of the ring under the applied load is measured by a micrometer screw and a vibrating reed mounted diametrically in the ring. The proving ring is generally calibrated at the National Bureau of Standards, where it is checked by dead weights to meet the requirements of Letter Circular LC 822.



(Courtesy Morehouse Machine Co., York, Penna.)

Figure 4. Proving ring.

Assuming the load to be within proper tolerance, it is next essential that it is not applied too rapidly, for this will add an extra load to the nominal load resulting from the inertia of the piston and weights and the friction of the plunger. This will increase the size of the indentation. Furthermore, too rapid application of the load will allow less time for the plastic flow of the material to take place, and thus will decrease the size of the indentation. The inertia effect is generally of greater magnitude insofar as the effect on the indentation size is concerned than the effect of plastic flow—especially as the inertia effect may be cumulative if it is necessary to build up the pressure more than once during the time of load application to keep the weights in floating equilibrium. The overload due to inertia may be reduced to a negligible effect if the load is applied smoothly, *i.e.*, if care is exercised in operating the pump, and if the machine is properly designed. If the rate of loading is uniform and does not exceed 500 kg/sec, no appreciable error will result from allowing insufficient time for plastic flow of the material to take place. This may be accomplished by observing the pressure gauge while applying the load.

The length of time for applying maximum load should be 30 seconds. This was recommended by Brinell and confirmed in a recommendation by the National Bureau of Standards (RP 903), where it is shown from tests on 29 ferrous and nonferrous metals that plastic flow is generally quite rapid during the first 30 seconds and much less so in the interval from 30 to 120 seconds. For the majority of metals the Brinell number varies less than 1 per cent for loading periods between 30 and 120 seconds.

It should be noted, however, that the British Standards Institute # 240 specifies that the full load shall be maintained for 15 seconds, and the A.S.T.M. E 10–27 requires that the load shall be applied for at least 10 seconds in the case of iron and steel, and for at least 30 seconds in the case of other metals. It was further pointed out in E 10–27 that with magnesium and magnesium alloys the minimum application time of 2 minutes should be used.

Hoyt found in testing copper that at the 30-second point the ball is still sinking into the surface. While Brinell and the National Bureau of Standards recommendation for a 30-second time application agree, it must be remembered that the Brinell test is a static test and the load should be applied until a constant-impression diameter is reached. In routine practice it may be proper, by mutual agreement or by making the test conform to a definite specification such as A.S.T.M. E 10–27 or B.S.I. # 240, to reduce the time for applying the load, but for research and scientific investigations equilibrium should be reached.

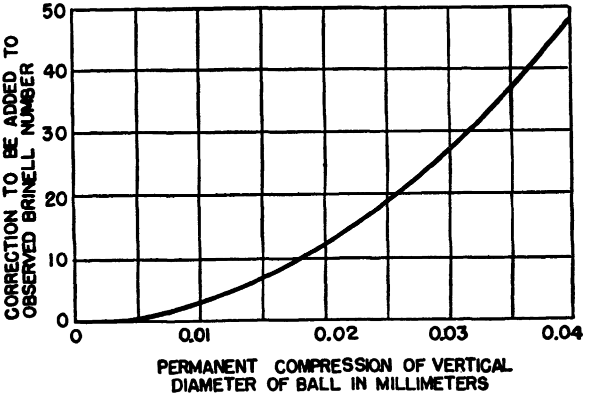
The Ball

Brinell used a 10-mm hardened steel ball as a penetrator. Here again there is considerable variation in the requirements for the ball size in different specifications. B.S.I. # 240 states that the diameter of the ball shall not differ from the appropriate standard diameter (10 mm in this case) by more than ± 0.0025 mm (0.0001 in.). A.S.T.M. E 10–27 specifies that the standard ball for Brinell hardness testing shall be 10 mm in diameter, with a deviation from this value of not more than 0.01 mm (0.004 in.) in any diameter, but the diameter of any ball measured at various points shall be constant within a permissible variation of ± 0.0025 mm (0.0001 in.). National Bureau of Standards RP 903 states that the difference between the average diameter and the nominal (10-mm) diameter of the ball should not exceed 0.025 mm (0.001 in.). It further states that the average diameter should be the average of six or more different diameters of the ball; moreover, the difference between any individual diameter and the average diameter of new balls should not exceed 0.025 mm (0.001 in.). The error in Brinell number due to variation in diameter of the most liberal of the three specifications referred to above would be negligible; therefore, the Bureau's recommendations are entirely adequate.

It is obvious that hardened steel cannot be tested by a hardened steel ball by the Brinell method, because the ball will flatten during penetration and a permanent deformation will take place. On the other hand, a hardened steel ball is entirely satisfactory in testing softer metals. This matter has received considerable thought and study since Brinell introduced his test, and is recognized in specifications for the test. An appreciable error will be introduced in the Brinell number for values over 500 when high-grade hardened steel balls are used. The deformation has the effect of increasing the diameter of the ball penetrator; this results in an impression of larger diameter, which results in a lower Brinell number.

Hultgren investigated this matter very thoroughly and developed a cold-worked steel ball, which was satisfactory for tests up to about 650 Brinell number. During the past ten years cemented carbide balls have been used and are recommended for Brinell testing of materials harder than 500 and up to about 800. Diamond balls have been investigated, but their high cost has prevented their general usage. The magnitude of error due to permanent deformation may be observed from study of the curve shown in RP 903 and reproduced here (Fig. 5) without showing the actual points. This curve is based on Hultgren's findings and also on additional work done at the National Bureau of Standards. It is a simple matter to determine the amount of permanent deformation in a 10-mm ball by simply measuring it with a 1-inch micrometer and reading to the nearest thousandth of an inch.

A clearer picture of this all-important factor in the Brinell test may be obtained from the manner in which it is discussed in specifications. The A.S.T.M. E 10–27 states that suitable balls shall not show a permanent change in diameter greater than 0.0025 mm (0.0001 in.) when pressed with a force of 3,000 kg against a piece of steel having a Brinell hardness number of 500 or greater. National Bureau of Standards RP 903 states that the material of the indenting ball must be specified in quoting Brinell numbers greater than 500. It adds that the permanent compression of the loaded diameter of the ball after any indentation on a specimen having a Brinell number less than 500 should not exceed 0.01 mm (0.0004 in.), but that if steel balls are used in specimens having Brinell numbers greater than 500, the permanent compression after any indentation should not exceed 0.025 mm (0.001 in.). "Carboloy" balls, or those made from other types of tungsten carbide, are recommended for indentations of any specimen having a Brinell number greater than 500.



(*From National Bureau of Standards RP 903.*)

Figure 5. Error due to permanent deformation of Brinell ball.

The British Standards Institution issues a separate standard entitled "The Hardness of Steel Balls for Brinell Hardness Testing" (No. 240, Part 2, 1929). This specifies the diamond pyramid hardness number (this test will be described later) for balls to be used in testing up to 630. For harder materials, the Brinell test is declared unreliable due to permanent deformation of the ball, and the use of the diamond indentation or other suitable test is recommended. An alternative method is offered for testing the hardness of the balls in cases where a diamond hardness testing machine is not available. Those desiring to study this more thoroughly are referred to this specification.

Good practice in Brinell testing today makes use of hardened steel balls or work-hardened steel balls, referred to as the Hultgren ball, up to about 500. For higher values other factors, such as the indistinct nature of the impression, may affect the test.

Much more difficult to visualize and study is the elastic or temporary deformation of the ball. The Brinell number is calculated from a formula referred to previously, and is a function of the diameter of the ball. If the ball were of rigid material and did not deform elastically under load, then the Brinell number as calculated from the diameter of the ball would be independent of the material of the ball. However, the ball does deform elastically under load to a considerable extent. Upon removal of the load, the ball, unless it has been deformed beyond its elastic limit, returns to its original shape or to at least within limits discussed previously.

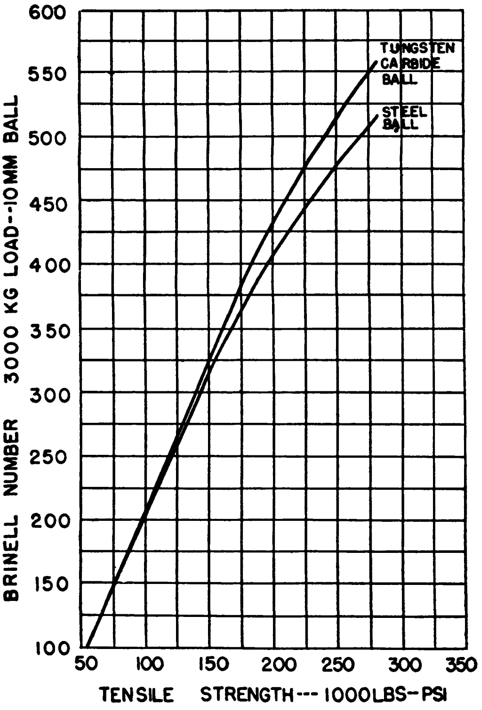
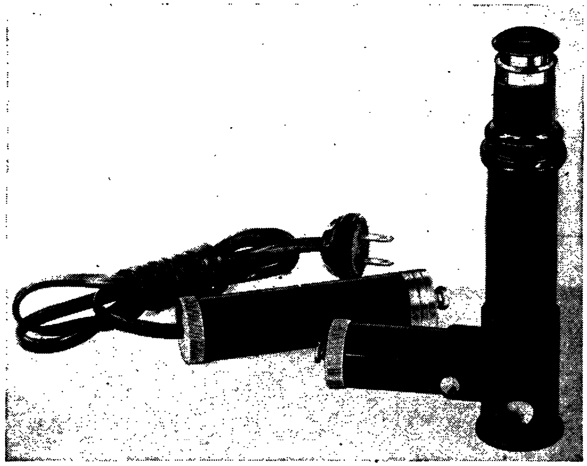


Figure 6. Difference in Brinell number using steel and tungsten carbide ball.

H. O'Neill,[1] who has made a very complete study of hardness testing, has shown that the elastic deformation of the steel ball in a Brinell test may amount to as much as 0.3 per cent. This is no disadvantage in the standard Brinell test with steel balls, as it is constant for a given load and hardness of specimen. The difficulty arises when other balls, such as cemented carbides, are used. The National Bureau of Standards has observed discrepancies as high as 70 Brinell numbers between "Carboloy" balls and steel balls. This was on hard material. Therefore, it is necessary to specify the material of the ball in quoting Brinell numbers over 500. Fig. 6 shows curves of Brinell numbers versus tensile strength for steel balls and tungsten carbide balls. These curves are not to be used for estimating tensile strength from Brinell hardness numbers, but are presented to show the effect of the material of the indenting ball.

Measuring Device

The diameter of the indentation is measured by a microscope (Fig. 7) to the nearest 0.01 mm (0.0004 in.). The error in reading the microscope should not exceed 0.01 mm, to keep the error in the Brinell number less than 1 per cent. A stage micrometer in the form of a disk is generally provided with the microscope and should be used frequently to check its adjustment. The above recommendations are from N.B.S. RP 903 and agree with A.S.T.M. E 10–27. B.S.I. #240 specifies measuring the diameter of the impression to within ±0.5 per cent and adds a note to the effect that an accuracy of measurement of ±0.025 mm (0.001 in.) may be accepted for impressions made with a 10-mm diameter steel ball. This would be satisfactory for Brinell numbers up to 500, using a 3,000-kg load. A miscroscope having a magnification of 20× is satisfactory. Artificial illumination may be secured by a small bulb, which admits light through an opening in the side, and an annular mirror, thus outlining the Brinell impression with good contrast.



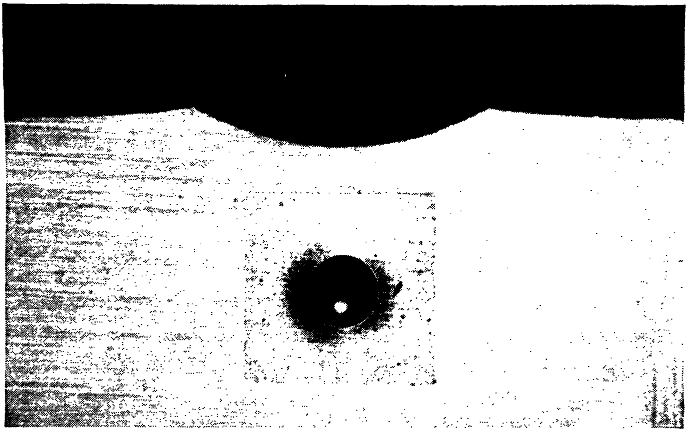
(Courtesy Bausch & Lomb, Rochester, N. Y.)

Figure 7. Brinell microscope. *Left:* Transformer and bulb for use on 115 v., a.c. *Right:* Microscope with dry battery attachment in place.

Test Specimen

The surface on which the Brinell impression is to be made should be filed, ground, machined or polished with emery paper (No. 000 emery paper is suitable) so that the indentation diameter is clearly enough defined to permit its measurement. There should be no interference from tool marks. Ordinarily there is no difficulty in so preparing a surface that the impression may be measured accurately to within 0.01 mm (0.0004 in.), as mentioned above. The surface should be representative of the material and not decarburized, case-hardened, or otherwise superficially hardened to any considerable extent.

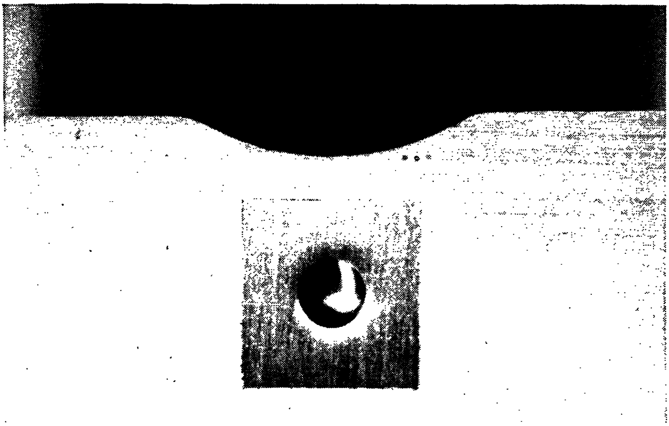
It has been observed since the introduction of the Brinell test that the impression may exhibit different surface characteristics. These have been carefully studied and analyzed. When some metals are tested there is a ridge around the impression extending above the original surface of the test piece (Fig. 8a); at other times the edge of the impression is below the original surface (Fig. 8b). In some cases there is no difference whatever (Fig. 8c). The first phenomenon is called a "ridging" type of impression and the second a "sinking" type. Cold-worked alloys generally have the former, and annealed metals the latter type of impression. The relationships of these types will be discussed later, but they are mentioned here as they influence the determination of the impression diameter.



(Courtesy R. H. Heyer)

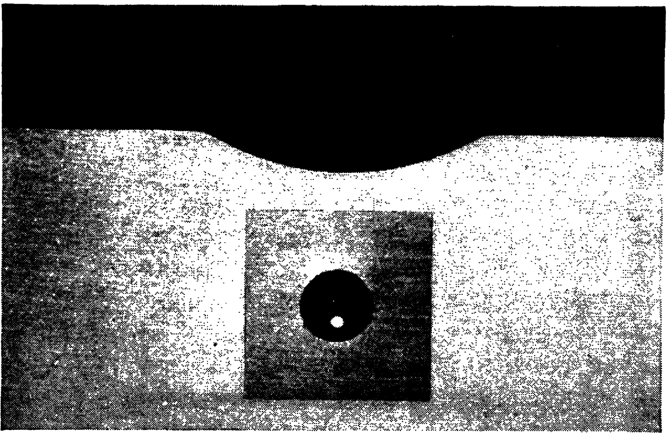
Figure 8a. Section and plan of a ridging type Brinell indentation. Diameter of indentation about 5.1 mm.

The definition of the Brinell number relates it to the surface area of the impression. To determine this, it is necessary to measure the diam-



(*Courtesy R. H. Heyer*)

Figure 8b. Section and plan of a sinking type Brinell indentation. Diameter of indentation about 5.1 mm.



(*Courtesy R. H. Heyer*)

Figure 8c. Section and plan of a flat type Brinell indentation. Diameter of indentation about 5.1 mm.

eter of the indentation, assuming that this is the diameter of the ind tation with which the ball was in actual contact. But in view of "ric ing" and "sinking" type impressions there is a question as to the ex part of the visible indentation with which actual contact was made. the case of "ridging" type impressions the diameter of the indentati is greater than the true value, whereas with "sinking" type impressio the reverse is true. This is obvious from the photographs. No way known of making certain that the correct diameter is measured, a the judgment and experience of the operator introduce a personal fa tor into the test.

In some materials the brink of the indentation is poorly defined, esp cially when hardened steels (even with polished surfaces) are testec the use of cemented tungsten balls produces a more distinct indenta tion. However, higher Brinell numbers will result in such cases becaus of the difference in elastic properties, as discussed previously.

The sharpness of the definition of the impression, especially in ver hard materials, may be increased by the use of a ball lightly etche with nitric acid. Considerable improvement in sharpness may be obtained by proper illumination. Often coating the material with a dul black pigment helps by leaving a clearly defined edge around the impression.

This matter of the indefiniteness of the edge of an indentation probably constitutes the greatest source of error between different operators of the Brinell test. Experienced operators will agree much more closely than inexperienced ones. National Bureau of Standards RP 903 indicates the average percentage error in the Brinell number for experienced operators to be less than 1 per cent, whereas inexperienced observers exceeded 2 per cent in some cases.

Brinell indentations made on some materials are far from round; those on materials which have been subjected to considerable rolling have impressions which are elliptical in shape, whereas those on heat-treated steels are quite round. For indentations which are not circular, an average value of the Brinell number may be obtained by measuring the diameter in four directions at approximately 45 degrees apart.

Indentations should not be made too close to the edge of a piece if accurate results are desired. Lack of sufficient supporting material on one side will cause the resulting impression to be large and unsymmetrical. It is generally agreed that the error in Brinell number is negligible if the distance from the center of the impression is not less than 2½ times, and preferably 3 times, the diameter of the impression from any edge of the test piece.

In like manner, indentations cannot be made too close to one another.

Under such conditions, the material may be cold-worked by the first indentation, or there may not be sufficient supporting material for the second identation. The latter condition would produce too large an indentation, whereas the former may produce too small an indentation. It is generally agreed in this case that the distance between centers of adjacent indentations should be at least three times the diameter of the indentation in order to have the error in the Brinell number of the order of less than 1 per cent.

The surface being tested must be normal to the penetrator. Tests conducted at the National Bureau of Standards indicate that an error of less than 1 per cent will probably not be exceeded if the deviation from normal is not greater than 2 degrees.

In a Brinell test there is an elastic recovery of the indentation after the load is removed. The resulting impression has a diameter greater than that of the ball (10 mm in the standard test), and the impression is generally spherical; the harder the material, the larger the diameter of the impression. Material having a Brinell hardness number of about 100 would require a ball a few tenths of a millimeter larger than 10 mm to fit the impression. Material having a Brinell hardness number of 400 would require a 12-mm diameter ball, while a material of 600 hardness would require a ball over 20 mm in diameter. This it must be remembered is from an indentation where the surface of the 10-mm ball made contact with the identation as the test was being made. In the Brinell test this is not of serious proportions when the diameter of indentation is measured and the spherical area is calculated from this measurement, especially for values under 500. If the spherical area were calculated from the recovered depth of the indentation, a large error would be introduced. The depth of the impression decreases while the diameter changes relatively little upon removal of the load. On material of Brinell hardness 600 which would require a ball over 20 mm in diameter to fit the recovered impression, the recovered diameter would be less than 10 per cent smaller than the diameter under load.

For testing soft materials a load of 500 kg is recommended, but the Brinell hardness number will vary considerably with the applied load. A well known example is "Armco" iron. When tested under a load of 500 kg it can be shown to be softer than drawn copper; but when tested under a load of 3,000 kg, it proves to be harder. Nevertheless, there is no agreement as to when the load in the standard test should be changed from 3,000 to 500 kg. A.S.T.M. E 10–27 recommends the 3,000-kg load for iron and steel and 500 kg for brass, bronze, and soft metals generally. National Bureau of Standards RP 903 states that 3,000 kg is the load commonly used for metals having a Brinell number greater than 100, and

500 kg for metals having a Brinell number less than 100. N.B.S. RP 185 indicates that changes to a load of 500 were made for metals with a Brinell number less than 70. The B.S.I. #240 provides a table showing a combination of loads, as well as different ball diameters, which will be discussed further in the next chapter. To avoid confusion and to enable different operators to duplicate results on the same material, the load applied should be stated. This is imperative when the load is other than 3,000 kg.' The relation between tests made with 500- and 3,000-kg loads is shown in Fig. 9.

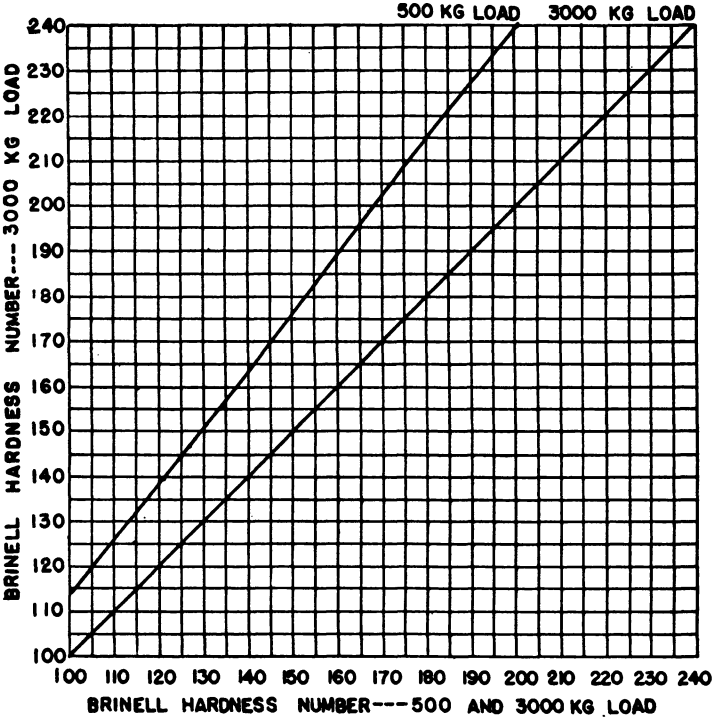


Figure 9. Difference in Brinell number using 500 and 3,000 *kg* load.

The load should be so selected as to keep the ratio of the diameter of the impression to the diameter of the ball greater than 0.25 and less than 0.50. For a ratio less than 0.25, the resulting impression is so small that errors in determining the diameter become a large proportion of the total diameter. Further, the test loses sensitivity and small differences in hardness values are not differentiated. For a ratio greater than 0.50 the test becomes supersensitive.

A load of 1,000 kg was formerly used to some extent in the United

States, but its current use is not in common practice. The minimum thickness of materials which can be tested with the Brinell method will be discussed in a later chapter.

The Depth Method

So far the standard Brinell test has been discussed and the many factors which influence the resulting number have been pointed out. In actual practice it is often desirable to make Brinell tests very rapidly, and many so-called Brinell testers in industry operate by measuring the depth of the impression instead of its diameter. Such tests are generally used for control purposes.

The depth of indentation is generally determined from the relative motion of the ball penetrator and the specimen. This is not the standard method, but a fair degree of accuracy may be obtained by making tests on several samples and reading the diameters of the indentations in the usual manner after the load is released. From these data a relation may be determined between a given depth of indentation and the Brinell hardness number. The depth of indentation may be taken either under load or after the release of the load, as the relation developed is purely empirical.

Equipment

From the foregoing it may be observed that the Brinell test is a ball, load and diameter specification. There are several types of testers manufactured for the determination of the Brinell hardness number. The one illustrated in Fig. 3 is manufactured by Aktiebolaget Alpha, Stockholm, Sweden, who is represented in this country by H. A. Holz of New York City. This company is the oldest manufacturer of Brinell hardness testers.

It is not necessary to describe all the various types and manufacturers of the Brinell tester, but some of the more commonly used instruments will be discussed. Many of these various makes operate on the same principle and vary in design only.

The Tinius-Olsen Testing Machine Co. of Philadelphia manufactures a complete line of hardness testers operating on the Brinell principle. Fig. 10 is an illustration of one of their hand-operated models generally used in laboratories and for small production requirements. It is a hydraulic press with a downward-acting ram applying the loads (500, 1,000, 1,500, 2,000, 2,500 and 3,000 kg) through the ball support to the ball indenter.

Fig. 11 illustrates a motor-driven production Brinell hardness tester recommended where high speed of operation is essential. The load is

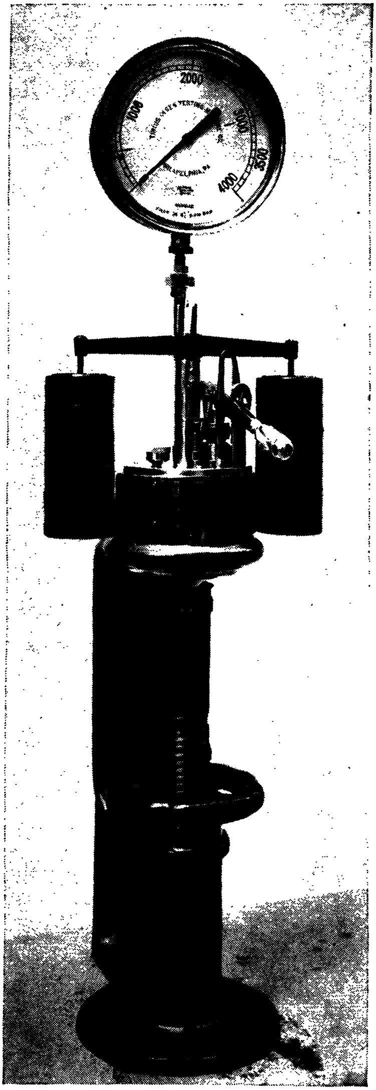


Figure 10. Hand operated Brinell hardness tester manufactured in the United States.

(Courtesy of Tinius Olsen Testing Machine Co., Philadelphia, Pa.)

applied by hydraulic pressure from a motor-driven pump. The load, varying from 500 to 3,000 kg, is applied to the work in less than three seconds by movement of an operating lever and is instantaneously removed by the same lever.

With both of the above models the Brinell impression is read by means of a microscope.

If it is desired further to speed up the testing and eliminate the reading of the impression diameter, a special machine is used (Fig. 11a). In this tester the upper dial indicates the load in kilograms applied to the ball. The lower dial indicates the depth of hardness impression. In actual production testing on identical parts, it is first necessary to make a few tests on the pieces and measure the diameter of the impression with a Brinell microscope to see if the material meets the required specifications. From these data the depth values are obtained and limits established on the depth gauge. If desirable, "go" and "no go" limits may be set up and production testing carried on rapidly. The load may be applied and removed in a few seconds. Speed of testing will depend on the ability of the operator to feed and remove work from the tester. This will vary with the size, shape and weight of the pieces.

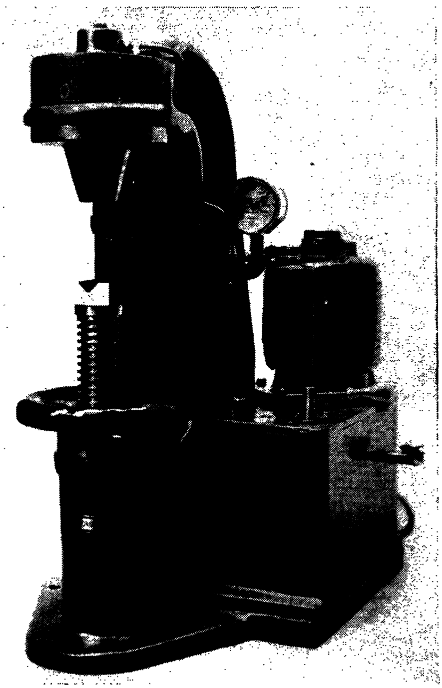


Figure 11. Motor driven Brinell hardness tester.

(Courtesy Tinius Olsen Testing Machine Co., Philadelphia, Pa.)

A dead-weight, fully hydraulic Brinell hardness tester, manufactured by the Riehle Testing Machines Division of American Machine & Metals, Inc., of East Moline, Illinois, is equipped with three cylinders, an accumulator cylinder for weighing and load maintenance, a main cylinder which transmits the load to the ball indenter, and a pump cylinder which delivers oil to the main cylinder. The pump plunger is actuated by the vertical handwheel through a pinion and gear. Loads of 500, 1,000 and 3,000 kg are available. They are applied by removing or adding calibrated accumulator weights. The loads are indicated by the rise of the weights. There is a spring connection between accumulator weights and accumulator plunger which causes weights to begin moving slightly be-

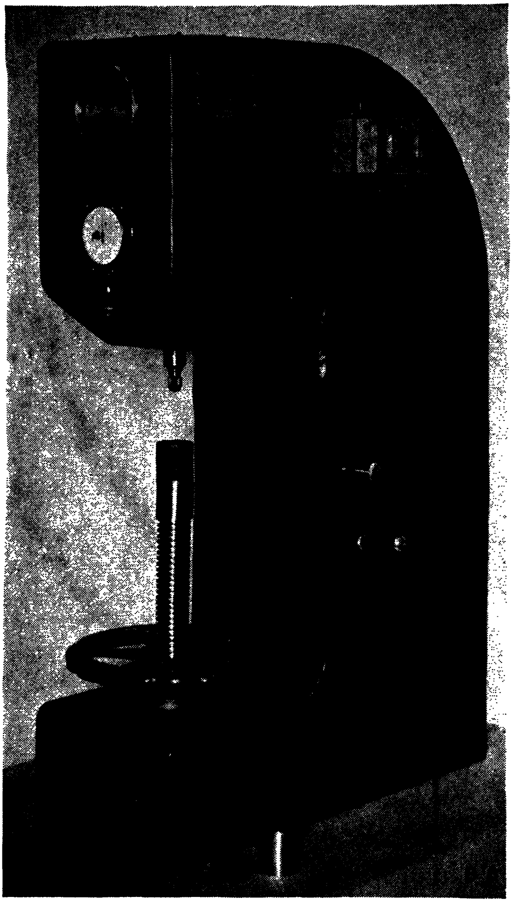
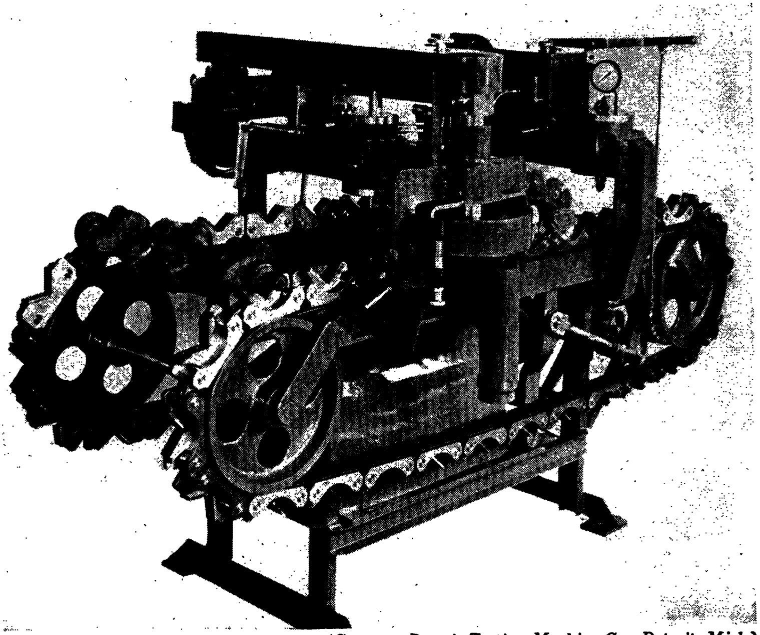


Figure 11a. Automatic Brinell machine.

(Courtesy Tinius Olsen Testing Machine Co., Philadelphia, Pa.)

low the maximum load; this overcomes inertia effects, as the weights are in motion at the time the maximum load is reached.

Special testers may be designed for testing pieces of irregular shape, and a few of these will be discussed. Fig. 12 illustrates such a machine arranged for testing automobile crankshafts, one of which is shown in the loading position. An endless chain of "V" links rides a rail on either side. These links are advanced one position at each revolution of the machine crankshaft; they stop under the grinding wheel, which is totally enclosed by a guard except for a notch which exposes a small surface of the wheel, and fits over the end of the work. As soon as the chain stops its forward motion, the wheel is lowered by a hydraulic cylinder to contact the work. A time factor governs the amount ground off and the wheel is raised to its original position. The chain then moves forward progressively until the ground spot is directly under the test-ball. Another hydraulic cylinder applies the test load. Again the chain moves forward until the crankshaft is thrown off on an inspection table.

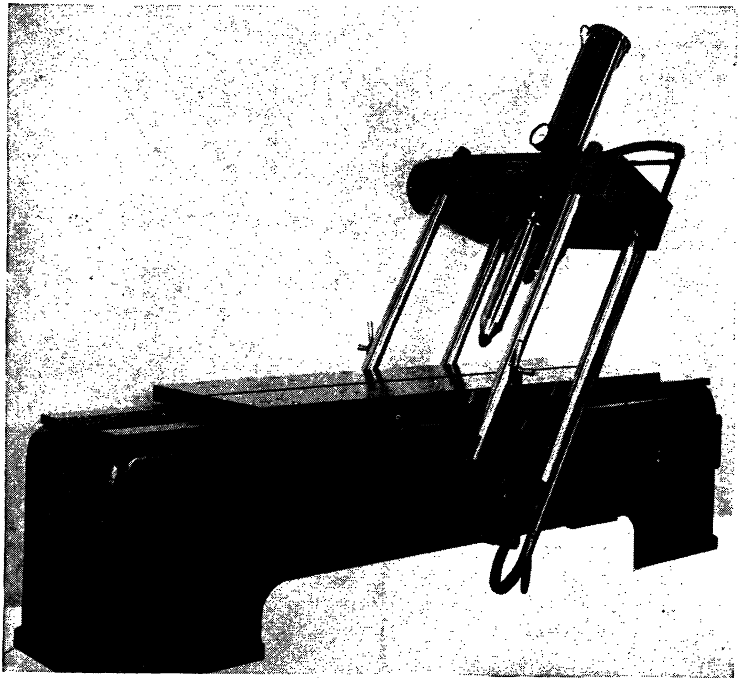


(Courtesy Detroit Testing Machine Co., Detroit, Mich.)

Figure 12. Automatic Brinell for testing automobile crankshafts.

The various cycles are controlled by the small cam, extending beyond the end of the machine crankshaft, which is connected to the operating valve. Action is automatic from loading position to inspection bench. The hand lever is used only when checking the test load. The machine handles 450 pieces per hour.

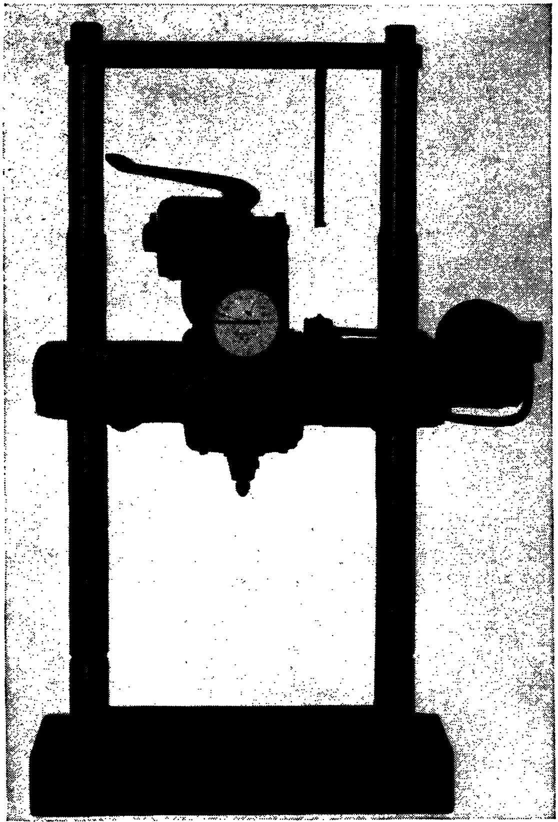
Fig. 13 shows a machine operating in much the same manner as a metal planer. The table moves forward and backward to position work under the rail, and a cylinder moves laterally across the work. Thus tests may be made at any point over the entire area of table. In addition, the cylinder may be tilted from the vertical position to 45 degrees. The tilting motion is controlled hydraulically by one of the levers shown on the side of the machine. The other lever controls the operation of the test cam. Other motions are push-button controlled. Dual controls are provided, permitting operation from either side of the machine. The machine shown is for testing large artillery projectiles. Tests are made on the outside diameter and at various points on the nose radius.



(Courtesy Detroit Testing Machine Co., Detroit, Mich.)

Figure 13. Planer type Brinell tester.

Figs. 12 and 13 illustrate machines for applying the testing load. The diameter of impression is read in the usual manner. Such machines are invaluable for production control, even though the length of time of application of the load and other factors are not in accordance with Brinell specifications. The error introduced is small in proportion to the value of the results obtained in testing pieces which at first might seem impossible or impractical to work with. These machines were built by the Detroit Testing Machine Company of Detroit, Michigan, which builds a complete line of Brinell machines.



(*Courtesy Steel City Testing Laboratory, Detroit, Mich.*)

Figure 13a. Brinell tester for testing large specimens.

Large, heavy pieces may be tested in an adjustable-head machine. Pieces up to 42″ wide and 52″ high may be tested as shown in Fig. 13a. The head is raised or lowered by push-button control. The pressure is applied hydraulically. There are a number of other standard and special types of Brinell hardness testers, but it would be repetitious to describe them all. Any omission does not imply in the slightest degree that the equipment is not equal or perhaps superior to the equipment described above. This description and the illustrations are intended to acquaint the reader with a few of the types of equipment available for making tests by the Brinell method.

Reference

1. O'Neill, H., "The Hardness of Metals and Its Measurement," Cleveland, Sherwood Press, Inc., 1934.

Chapter III

Meyer's Analysis

When the Brinell test is analyzed, it is found that the selection of the spherical area of contact by which to divide the load is a satisfactory one, although it would have been far more rational to use the projected area. By his selection, Brinell obtained nearly constant values for steels for loads of from 500 to 3,000 kg; later, however, others found rather large differences for some soft metals. Experience has shown the test to be valuable for inspection of materials and control of processes and compositions. The significance of the ball test calls for a careful analysis. Brinell attributed the variation in his hardness number with testing load to different degrees of cold-working during application of the load.

The measurement of the impression and the calculation of the number are not based on the hardness of the metal before it was cold-worked or strained by the ball, nor yet on the hardness of the metal after it was strained the maximum amount at the completion of the test. Rather there exists a complex pattern of stresses under the ball, and this pattern changes during application of the load. In addition, the metal itself changes due to work-hardening. All these factors have a bearing on the hardness values obtained.

Professor Eugene Meyer of the Materials Testing Laboratory at the Imperial School of Technology, Charlottenburg, made an intensive study of the Brinell ball indentation hardness test and published his results in 1908.[1] Inasmuch as his work served as the basis for considerable research carried on by students of hardness testing, and also is responsible for many of the present thoughts in connection with indentation hardness, it will be explained briefly and an example given to show how the Meyer constants may be determined mathematically and graphically.

Meyer's work showed that resistance to penetration by a ball penetrator varies with the degree of penetration of the ball and follows the relation

$$L = ad^n$$

where L = load in kg

d = diameter of indentation in mm

a and n are constants of the material under test

Hoyt,[2] in an excellent study of Meyer's work, defines the constants as follows:

a = resistance of the metal to initial penetration
n = measure of effect of the deformation on the hardness of the metal

It is obvious, although often overlooked in practice, that in a penetration hardness test the hardness of the metal is affected during the test, and the amount of change will depend on the metal and its condition. Meyer's work confirmed this for the ball test; moreover, once the constants a and n are determined, information is available concerning the hardness of the virgin metal and also the effect of the indentation process. Such information could never be obtained from a single hardness number. Meyer investigated 18 metals ranging from lead to steel, and thus his work covered a rather complete range.

Meyer realized that the Brinell number was influenced by the geometry of the ball as well as by the resistance of the metal to penetration. He made the intelligent recommendation that a number representing the mean pressure supported by the metal be adopted; this he designated as P_m. It was obtained by dividing the load by the projected area of the impression and is known as the Meyer hardness number. By formula,

$$P_m = \frac{L}{\frac{\pi d^2}{4}} = \frac{4L}{\pi d^2}$$

where L = load in kg
d = diameter of indentation in mm

Hoyt's work[2] shows this very nicely; Fig. 14 shows results of tests made on annealed copper with a 10-mm diameter ball under various loads. Curve 1 shows how the diameter of the impression increases as the load on the ball is increased; curve 2 shows the hardness number as determined by the Brinell formula. It will be noted that the hardness number increases to a maximum as the load is increased, and then falls off at high loads, which is not consistent with the true resistance of the metal to penetration. Curve 3 shows the mean pressure values as used by Meyer; this "Meyer hardness" increases continuously with the load. In these tests, the ball was allowed to come to equilibrium before the load was removed. Meyer's work thus emphasizes why the Brinell values obtained at 3,000 kg do not always agree with values obtained at 500 kg. It throws light on why Brinell was practically forced to select the surface area of the indentation in his attempt to obtain a single number for his hardness value and to have the number as free from anomalies as possible. Had Brinell investigated copper in the cold-worked condition, he would have observed a definite falling off of hardness at loads up to 3,000 kg.

It might have been better had Brinell adopted the more rational mean pressure value, as suggested by Meyer and confirmed by Hoyt; but as mentioned before, the Brinell hardness number, as adopted, seems to have worked out as a good practical test.

Meyer's formula ($L = ad^n$) shows some interesting facts. If the diameter of the impression is 1 mm, the constant a is the load in kilograms required to produce the indentation. When a 10-mm diameter ball is used, a 1.0-mm diameter indentation represents a very small permanent deformation; hence the cold-working effect is small and the constant a is an indication of the initial or unworked hardness.

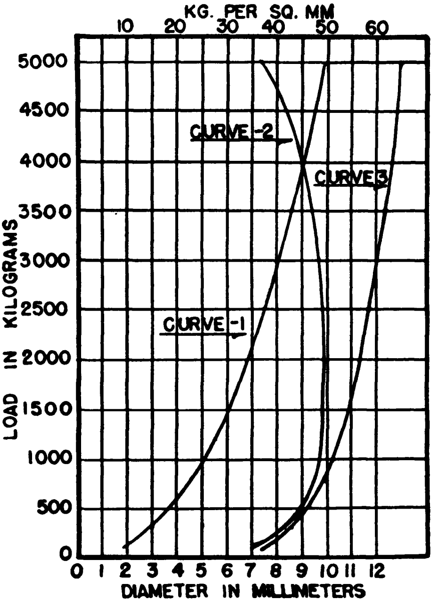


Figure 14. Brinell tests on annealed copper.

The values of the constant n vary from approximately 2.0 for cold-worked materials to 2.5 for materials in the dead-soft condition. Materials which have been cold-worked and having an n value of 2.0 have little capacity for additional cold work, whereas dead-soft materials with an n value of about 2.5 have very high capacity for cold work.

Determination of Meyer Constants

The Meyer constants a and n for a particular metal may be determined mathematically by simultaneously solving two exponential equations.

Let us assume that a metal when tested with a load of 125 kg has an indentation diameter of 2.1 mm, and when tested with a load of 1,000 kg it shows an indentation with a diameter of 4.9 mm. Then

$$\begin{aligned} 125 &= a2.1^n \\ 1000 &= a4.9^n \\ \log 125 &= \log a + n \log 2.1 \\ \log 1000 &= \log a + n \log 4.9 \end{aligned}$$

using 5 place logarithm tables

$$3.00000 = \log a + 0.69020n$$

Subtract

$$\underline{2.09691 = \log a + 0.32222n}$$

$$0.90309 = \qquad 0.36798n$$

$$n = \frac{0.90309}{0.36798} = 2.4542$$

then

$$\log 125 = \log a + 2.4542 \log 2.1$$

or

$$\begin{aligned} \log a &= \log 125 - 2.4542 \log 2.1 \\ \log a &= 2.09691 - 2.4542 \times 0.32222 = 1.30611 \\ a &= 20.235 \end{aligned}$$

$$n = 2.45 \quad \text{and} \quad a = 20.2$$

In the graphic solution plot the two points representing two impressions on logarithmic paper, using the loads as ordinates and the diameters as abscissae. Join the points by a straight line. Actually one or two intermediate points should be used as a check.

From the plot (Fig. 15) the value a is determined by extending the line through $d = 1$, for then $L = ad^n = a$, and a may be taken directly from the L scale; n equals the natural tangent of the slope of the line.

From the plot $a = 20$ and the slope of the line is 67°50′, of which the natural tangent is 2.4545, or $n = 2.45$.

Geometrically Similar Impressions

Meyer has shown that equal hardness numbers, P_m, are obtained when using balls of different diameters, provided the loads used produce geometrically similar impressions, which have equal impression angles. The impression angle in the ball test is defined as the angle between the center of the ball and edge of the impression (Fig. 16). Under conditions of geometric similarity, the stress distribution pattern would be the same, but the strains will increase with increase in the size of the ball.

If equal mean pressure and equal impression angles are to be obtained, then L/D^2 must be a constant, which is true when $L_1{:}L_2{::}D_1^2{:}D_2^2$, or

$$L_2 = \frac{L_1 \times D_2^2}{D_1^2}$$

where L_1, L_2 and D_1 and D_2 are the loads and ball diameters, respectively. The ratio is often applied to the Brinell test, and it appears to hold in

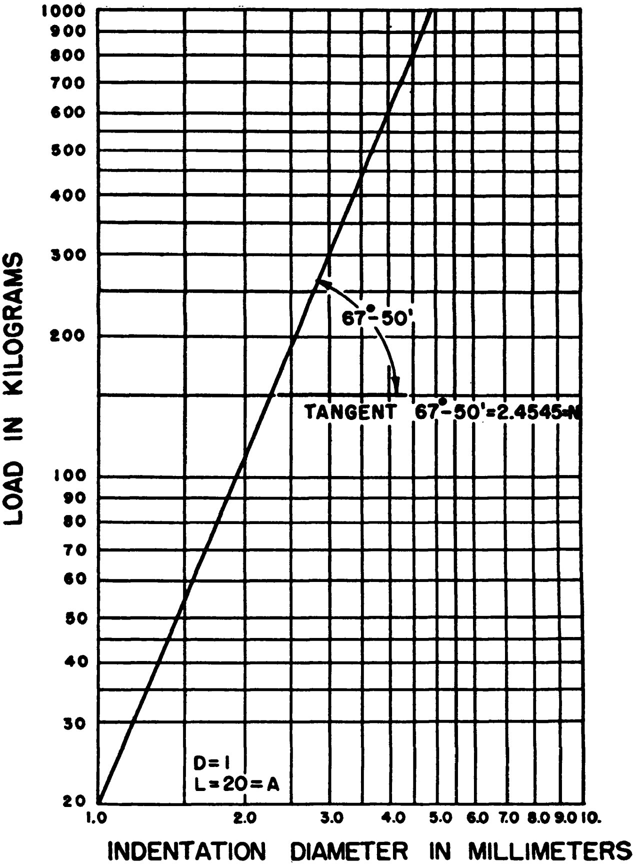


Figure 15. Determination of Meyer constants for graph.

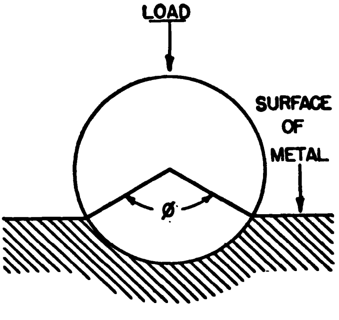


Figure 16. Impression angle.

general. To obtain hardness numbers corresponding to those obtained with the standard tests the ball diameter relationships should be:

$$L_2 = \frac{3000}{100} \times D_2^2 = 30D_2^2 \quad \text{for the 3,000-kg and 10-mm ball test}$$

$$L_2 = \frac{500}{100} \times D_2^2 = 5D_2^2 \quad \text{for the 500-kg and 10-mm ball test}$$

This principle is generally accepted in Brinell testing and is recognized in A.S.T.M. E 10–27 and B.S.I. #240. The latter recommends different values of L/D^2 for different materials and further states that it is advisable that the ratio of the diameter of the impression to the diameter of the ball generally not fall below 0.25 nor exceed 0.50. For a given specimen geometric similarity follows with the proper L/D^2 ratio. But with different hardness values of the same material considerable geometric dissimilarity is permitted with the 0.25 to 0.50 limitations when using the same load and penetrator. This is unavoidable if a ball penetrator is used. Geometric similarity does not exist between tests made with 500-kg and those made with 3,000-kg loads.

To keep within the 0.25 to 0.50 limits, B.S.I. #240 recommends four L/D^2 ratios as follows:

Material	L/D^2
Steels and cast iron	30
Copper alloys and aluminum alloys	10
Copper and aluminum	5
Lead, tin and tin alloys	1

In the United States, ratios of 30 and 5 are the ones generally encountered; the former for iron and steel and the latter for brass, bronze and soft metals. Once the L/D^2 ratio has been selected so as to keep within the limits of impression diameter to ball diameter, it may be necessary to use lighter loads and smaller diameter balls because of sample thickness. Under such conditions geometrically similar indentations and consequently corresponding hardness values for that particular series of tests are obtained if the L/D^2 ratio is maintained. Maintenance of geometric similarity over a range of materials is possible only with cone- or pyramid-shaped indenters.

Application of Meyer's Analysis

Meyer's work, carried out using a ball indenter, has been instrumental in giving a much clearer picture of the mechanics of the ball test, especially the role of work-hardening capacity or strain-hardening ability of a metal. In actual testing in laboratories and shops, Meyer's analysis is seldom heard of because of the complications in carrying out such testing.

Hoyt gives an example of the type of information which could be obtained through the use of Meyer's data. A bar of cold-rolled copper has a higher Brinell number than a bar of annealed steel, but the steel will scratch the copper and in turn will not be scratched by the copper. The question arises as to which is the harder. Meyer's analysis gives the answer—both. At low loads the copper is harder, and at high loads the mild steel.

R. H. Heyer[3] has investigated the cause and significance of the difference in impression contours observed in ball indentation tests. The "ridging"-type contours are associated with metals having low Meyer *n* constants, hence low work-hardening capacity. The "sinking"-type contours are associated with high Meyer *n* values (2.3 and over) and high work-hardening capacity. It is shown that consideration of the type of indentation contour is useful in making hardness conversions from one scale to another. The minimum thickness of metal that can be tested in a Brinell test is also influenced by the type of indentation. For example, a 5.0-mm diameter indentation of the "ridging" type associated with a Meyer *n* of 2.00 to 2.15 produces readily measurable permanent deformation at $\frac{3}{16}$ in. below the surface, whereas the same size indentation produces an equal deformation at $\frac{3}{8}$ in. below the surface if it is of the sinking type associated with a Meyer *n* value of about 2.45. Thus a 5.0-mm diameter indentation could safely be placed in a $\frac{1}{4}$-in. thick plate in one case, but not in the other.

Ludwik Cone Test

In an effort to simplify the Brinell test and to make the hardness number independent of the load and the dimensions of the impression, Ludwik[4] proposed the use of the cone test. It will be considered at this time because it produces geometrically similar indentations, and the test has been subjected to an analysis similar to that of Meyer.

Ludwik's cone-test hardness of a material is obtained by dividing the load applied to the material by the area of the conical indentation; the depth of indentation is measured. The test may be carried out with the same type of apparatus used for ball tests. The area of indentation is calculated from the measured values of the depth of indentation.

Ludwik worked with loads of 500 to 3,000 kg, depths of 1 to 3 mm, and cone angles of 60, 90, and 120 degrees. His investigations covered tests on iron and steel. Considerable ridging of the metal about the cone was encountered. This immediately raised the question as to the proper depth of the indentation, *i.e.*, from the original surface or from the top of the ridge.

Ludwik measured the depth of indentation from the surface of the material, and not from the top of the ridge. He used 90° cones for most of his work, and obtained hardness numbers which were fairly consistent in value irrespective of the load. By formula

$$\text{Ludwik cone hardness} = \frac{\text{load}}{\text{conical contact area}} = \frac{4L \sin \alpha /2}{\pi d^2}$$

L = load in kilograms
d = diameter of indentation in mm
α = cone angle

Using Ludwik's 90° cone angle, and measuring the depth of indentation t in millimeters, then

$$\text{Ludwik cone hardness} = 0.225 \frac{L}{t^2}$$

Devries[5] carried out tests using cones of 60 and 90 degrees on copper, iron and steel, and found that the relation between load and depth followed the general formula $P = at^n$, where P is the load applied to the cone in kilograms, and t is the depth of indentation from the original surface of the metal, measured from the movement of the cone into the metal under load. This work indicates that the hardness number decreases rapidly with increasing load. The cone-test hardness number therefore has a limited application, since it is not independent of the load and the dimensions of the impression. The relation between load and depth as determined by Devries is shown in Fig. 17.

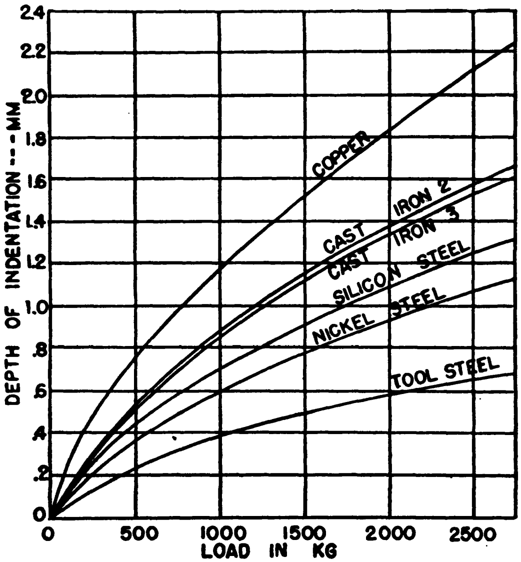


Figure 17. Relation between load and depth of indentation in cone test as determined by Devries.

Ludwik was evidently aware of decreasing hardness values with increasing loads. In a footnote to his work he suggests that his depth readings may be erroneous, and that more careful depth determinations may show a falling off in hardness values at high loads.

O'Neill,[6] however, states that the hardness number will be practically independent of the load, if the measurement of the diameter or depth of the indentation also includes any piled-up ridge present.

Further investigation along this line is needed, if it is to be definitely ascertained that the cone hardness number expressed as a load, divided by area relation, is independent of the load. This work should be carried out with modern hardness-testing equipment, using diamond cones; the area of indentation should be determined from both depth and diameter measurements which take into consideration the original surface of the metal as well as the top of piled-up ridge. It should be kept in mind that true geometric similarity is achieved only by using cone- or pyramid-shaped indenting tools. Cones bring about uniform plastic flow and consequent uniform strain-hardening. Therefore, conical indenters are a possibility for true, comparative results independent of the load.

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Chapter IV

The Scleroscope

The Scleroscope was invented in 1906 by A. F. Shore during his search for a method of testing hardened steel. The Brinell method could not be applied because of the flattening of the steel ball, and cemented carbide balls were then unknown.

In the Scleroscope test, a diamond-tipped hammer inside a graduated glass tube falls, under the force of its own weight, from a fixed height onto the test specimen, and the resulting rebound is read on a graduated scale. The height of the fall is 10 inches; the diameter of the hammer a little less than ¼ by ¾ in., and its weight about 1/12 ounce. The shape of the diamond is slightly spherical and blunt, with an approximately 0.020-in. diameter. The diameter varies slightly with different hammers to allow for differences in coefficient of restitution.

The Scleroscope is considered an indentation hardness tester, as its hammer is rounded to permit penetration into the specimen; the test is dynamic, inasmuch as rapid indentation is involved. Prior to Shore's work, R. Martel[1] studied dynamic hardness testing, and reported that the volume of indentation produced by a falling hammer was proportional to the height of the fall and the mass of the hammer, and independent of its shape. Later it was shown that this conclusion was not entirely true, but Martel's work is important and O'Neill cites him as laying the foundations of dynamic hardness testing.

The scale of rebound in the Scleroscope is arbitrarily chosen and consists of units, divided into 100 parts, which represent the average rebound from hardened, pure, high-carbon steel. The scale is continued higher than 100 to include metals having a greater hardness than fully *hardened high-carbon steel. The value of 100 as the hardness number of hardened high-carbon steel was chosen as the most convenient.*

The force developed in testing hardened steel of 100 numbers is about 500,000 pounds per square inch. The size of the permanent indentation is comparatively negligible, but definite; it increases when softer material is tested. This relationship may be expressed mathematically by the striking energy divided by the depth size of the impression to obtain the average pressure caused by impact.

On very hard steel the rebound is about 90 per cent of the fall, provided no impression is made. Some of the striking energy is absorbed in the indentation made with a round hammer; if a rebound of 75 per cent of the energy is obtained, then 15 per cent (90 minus 75) is spent in indenting the specimen before it bounces back. The rebound is caused by the elasticity of the material; the higher the elastic limit or ultimate strength of the material, the greater the rebound.

Apparatus

Two Scleroscope testers manufactured by the Shore Instrument & Mfg. Co. are available: models C and D. Model C (Fig. 18) is designated as the direct-reading type; the moving part consists of a diamond-tipped drop hammer held in position on hanger hooks at the top of a glass tube graduated into 140 divisions. The hammer is dropped by pressing a hand bulb which opens a valve; two oscillating hooks release the hammer, which falls on the surface being tested, and rebounds immediately.

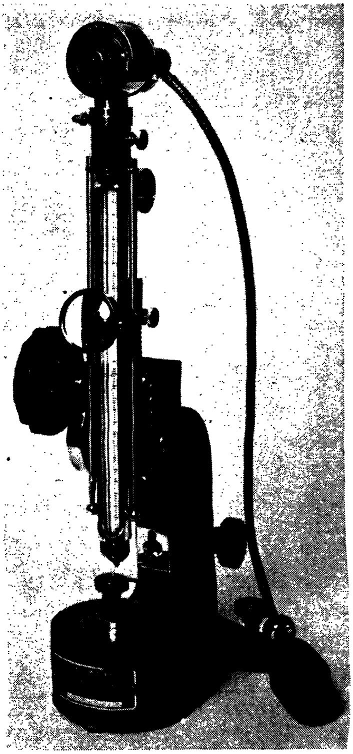

Figure 18. Model C direct-reading Scleroscope.

(Courtesy The Shore Instrument & Mfg. Co., Inc., Jamaica, N. Y.)

When the bulb is pressed again, the valve under cam action places the glass tube chamber in suction communication with the bulb; the vacuum created when the bulb is released sucks up the hammer, which is caught by the hooks and held ready for the next test. A little practice is required to enable the operator to manipulate the bulb so that the alternate pressings will release the hammer, allow it to rebound, and catch it again before it strikes the test piece a second time.

Experience is also necessary to read the Scleroscope accurately. The indication or number is the height of rebound of the top of the hammer, and

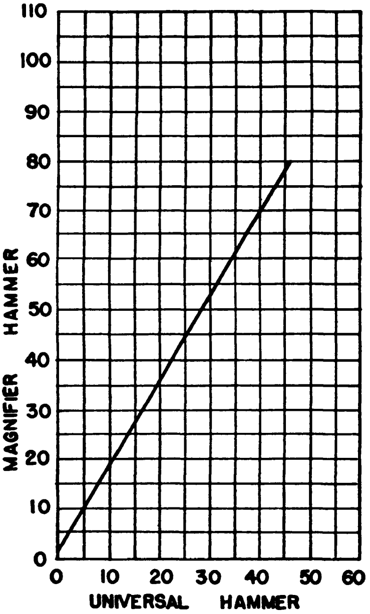

Figure 19. Relationship between universal hammer and magnifier hammer.

the operator must read the position on the scale the moment the hammer comes to rest at the top of the rebound before the hammer starts to drop again. Often two or three tests must be made to obtain a correct reading. Hard steel tests about 100; medium hard about 50, and soft metals 10 to 15. Knowing these approximate values, the operator focuses his vision at about these numbers on the scale.

The Scleroscope is set up about level, as indicated by a plumb rod built in the instrument. The surface being tested must be level and normal to the tube. For soft metals a surface prepared with a No. 2 or No. 3 file is satisfactory, while hardened steels require a surface prepared with a medium fine emery wheel. This is explained a little later.

When testing soft metals, the rebound of the hammer is small; to increase this, a steel magnifier hammer with a larger point area is furnished. In this way a higher rebound magnifies small but significant changes in hardness. When using the magnifier hammer, special note should be made to differentiate the readings from those obtained with the diamond-tipped or "universal hammer."

A chart showing the relation between values obtained with the universal hammer and the magnifier hammer is shown in Fig 19.

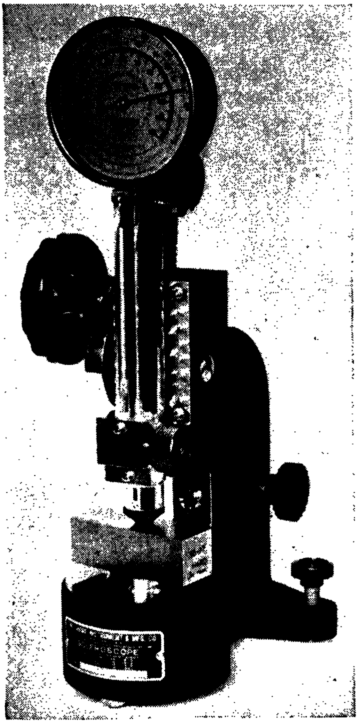

Figure 20. Model D dial recording Scleroscope.

(Courtesy The Shore Instrument & Mfg. Co., Jamaica, New York)

The Model D Scleroscope (Fig. 20) is known as the dial-recording Scleroscope and was designed to record the indications of model C. This is accomplished by the use of a longer and heavier hammer, which develops the same striking energy by falling through the very short distance of only ¾ inch. The rebound is locked and recorded by means of a ball and hollow cone clutch. In Model D, only the universal hammer is used. The manufacturer claims that both C and D models give the same values for a particular metal with the universal hammer.

The operation is very simple. The hammer is elevated, released, and dropped by turning a control knob in a clockwise direction for about ⅝ turn until an internal stop is reached. At this point rebound occurs and the hammer is locked at its full height in a clutch. When the control knob is returned to its original position, the clutch is raised and brought into contact with an indicator rack actuating rod which records a reading on the dial in proportion to the height of the hammer's rebound. The indicator dial point remains fixed at the hardness number until the cycle is repeated for another test.

Test surface finish and leveling require the same attention in Model D as in C.

Conversion from one hardness number to another will be discussed in a separate chapter but it is well to point out here that the Model D Scleroscope has a second scale on the dial which gives equivalent Brinell hardness numbers. The Brinell values are given for a hardened steel ball up to 400 to 500, and above these values are those obtained with a tungsten carbide ball.

Standardization of Testers

The accuracy of the Scleroscope is checked by means of master blocks of both hard and soft steel marked with the known Scleroscope hardness number. Instruments in good condition should show an accuracy of 95 per cent of the value marked on the block. Several readings should be taken and averaged.

Factors which affect the accuracy of the test and hence the agreement between different operators at different places may be listed as follows:

(1) Plumbness of the instrument at the time of hammer drop.
(2) Effect of lateral vibrations or shocks on the hammer.
(3) Smoothness of surface of the test specimen.
(4) Condition of the diamond in the hammer.
(5) Effect of mass on the test specimen.
(6) Thickness of the test specimen.
(7) Effect of testing near the edge of the test specimen.
(8) Effect of curved surfaces of test specimens.
(9) How test specimens are held or mounted.

The effect of each will be discussed separately.

The instrument must be set or held as perfectly plumb as possible and within one degree, to prevent inaccuracies from this factor. For each degree out of plumb, whether because of tilting of the instrument or the tapered surface of the test specimen, the error may be obtained from the values in the following table. These values apply to both C and D models.

Lateral vibrations from shocks or other causes introduce considerable error because they tend to throw the tester out of plumb, and if there is sufficient movement to cause the plumb rod to rattle, there will be ap-

Scleroscope Errors for Vertical Deviation

Deviation from Vertical (Degrees)	Rebound Loss (Per Cent)
1	1.0
2	2.5
3	4.5
4	7.0
5	10.0
10	33.0

preciable error. This condition must be observed when freehand tests are made.

Rough surfaces cause fluctuations in readings. The surface should be filed with a No. 2 or 3 file to obtain correct readings. Soft steels show a drop in reading of from 3 to about 10 per cent when polished with coarse emery stones. By polishing with smoother wheels or emery paper, the percentage variation is reduced as well as the amount of error.

A highly polished hardened steel surface which tests about 100 will drop from 94 to 98 when ground with a rough emery wheel. By the use of smoother wheels and emery paper, the original value of 100 may be obtained. The assumption, of course, that the surface of test specimen is not changed in hardness while being polished, is very broad, and errors of large proportions may be introduced in polishing specimens.

The diamond point may become worn or broken, and if low readings are obtained on the master blocks, the diamond should be examined under a magnifying glass or check tests made with a hammer known to be in good condition.

It is fully recognized that the mass of a specimen being tested in the Scleroscope has an appreciable effect on the accuracy of the test. The specimen must be in the form of a cube weighing at least one pound before its inertia is large enough to resist the force of the falling hammer sufficiently to cause the height of the rebound to be independent of the method of support. As the mass decreases, compensation must be made for any deficiency in the specimen itself, by properly supporting or clamping during test. The softer the material, the greater the error due to insufficient mass because of the deeper indentation and greater time factor necessary to penetrate softer materials.

Specimens of Scleroscope hardness 100, weighing ½ pound, will have an error of ½ to 1 per cent, and 2 per cent if the material is only 20 numbers hard. If the weight is reduced to ¼ pound, the error increases to 2 or 3 per cent and 4 per cent, respectively, while in a piece weighing 1 ounce the error reaches proportions of 20 per cent and 40 per cent.

To overcome the lack of mass in underweight objects, the necessary mass and inertia must be provided by means of a clamping device. The fundamental requirements are such that the supporting contact surface is perfectly flat and free from dust or oil film. It has been shown that material $\frac{1}{16}$ in. thick, ground smooth so as to lie perfectly flat, and clamped to a supporting anvil block, has practically no loss in rebound. Commercially ground surfaces show a small error.

When placed in a V block, small cylindrical specimens show appreciable error up to $1\frac{1}{4}$ in. in diameter owing to lack of proper support beneath the striking point. By preparing a special grooved block (Fig. 21) so that support is provided directly underneath the area struck by the falling hammer, the error is reduced by about 50 per cent. Special methods must be provided for clamping and supporting balls while they are being tested, the best results being obtained by supporting as shown in Fig. 22.

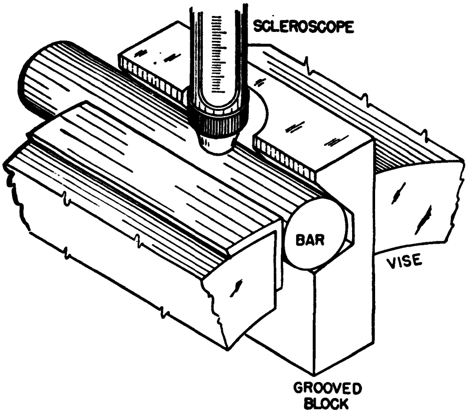

Figure 21. Support for small cylindrical specimens.

Considerable research has been done on the proper clamping of thin specimens, cylindrical pieces, balls and underweight objects. Such devices as backing up the specimen with different materials, using a hard supporting anvil, mounting small-diameter balls in solder, etc., have been studied. It may be concluded generally that in each case of testing thin material and round parts there is some means of giving correct readings if the parts are properly supported and clamped, but each thickness, hardness and radius of curvature must be studied as an individual problem. The introduction of other methods of hardness testing which are not affected by mass of the material, as they do not operate on the rebound principle, has greatly simplified the problem of testing material less than one pound weight in compact form. The effect of thickness, other than its influence on the mass of the specimen, will be discussed in the chapter on testing sheet metal.

Flat and parallel specimens may be tested near the edge, provided the sample is properly clamped. In addition to supporting cylindrical and spherical specimens so that they have proper under-support, it is also necessary that the hammer strike the top of the radius. A later chapter will discuss the testing of cylindrical surfaces.

Thin materials or underweight objects require clamping to acquire or borrow the inertia of the support; the sound of the impact should tell the operator when correct support is obtained. A dull thud indicates proper support, whereas a shrill note shows that the piece being tested has not acquired sufficient mass from the support. A vertical clamping stand provided with the instrument may be of advantage for clamping sheet metal and cylindrical parts. In its use pressure must be maintained while the test is being made, to insure perfect contact with the supporting anvil.

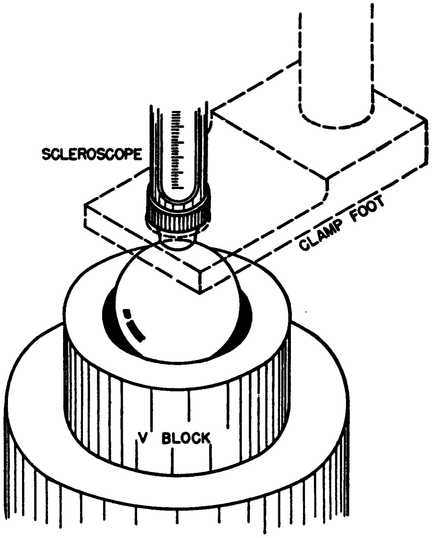

Figure 22. Support for ball.

Large pieces may be readily tested in the Scleroscope by setting it on top of the piece. Irregularly-shaped pieces may be tested by holding or clamping them on a special fixture. The instrument is quite flexible in this respect. Both models are furnished with a swing arm for testing in a bench vise or plate.

When using either model of the Scleroscope, specimens should be supported in such a manner as to obtain the highest rebound. Such readings are the most accurate. Occasionally it will be found that higher readings are obtained on the D than the C model, or vice versa, although both instruments show the same results on master blocks. The higher reading is nearer correct. This variation may be caused by the difference in the mass of the hammer in the two instruments; the hammers rebound in different percentages because of support or other factors. One such factor is the rate of vibration of tubing or cylindrical parts with thin wall thicknesses. Different vibration rates interfere with the rebound of hammer of different weights. Such vibrational effects may be reduced by the method of holding the hollow piece during test. Insertion of plugs or mandrels are often helpful. Vibrational effects are generally not present in specimens other than hollow parts.

The Scleroscope is exceptionally fast in operation, portable in that it may be used for testing large and heavy pieces or specimens clamped in a vise and, except for the limited application of the magnifier hammer in Model C, has only one scale.

The user must be cautioned on the effect of mass of small pieces, and the personal element involved in using the direct-reading Model C. The recording model should be checked frequently on master blocks to make sure errors caused by friction are not present.

Reference

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Chapter V

The Rockwell Tester

Indentation hardness testing by the Brinell and Scleroscope methods grew in importance and during World War I practically all hardness testing was done on either one or the other of these two instruments or by the file test, which will be discussed later. During the period from 1910 to 1920 tremendous growth was taking place in the United States insofar as industry was concerned. This period marked the birth of the vast mass production system as it is known today, which developed primarily through the growth of the automotive industry. Great strides were also made in the use of alloy steels, with the result that a demand was created for more and more hardness testing, especially of finished parts and for process control.

The Brinell test was too slow for testing in the shop, although it was accepted by the laboratory; furthermore, the impression was too large to use on finished parts. It could not be used on fully hardened steel and the results were dependent, to a certain degree, upon the skill of the operator in reading the diameter of the impressions. It was necessary to grind or prepare the surface where the test was to be made to obtain a good, clear impression for the operator to read. For these reasons, this instrument could not meet the requirements of large inspection departments or heat-treating rooms in mass production plants.

The Scleroscope was fast but, as was pointed out, a skilled operator was necessary to read the rebound, and different operators obtained different results. The recording-type instruments gave varied readings, probably because of friction in the clutch mechanism. Fully as important was the variation in readings owing to the mass of the piece being tested. Because of its speed and the fact that it could be used in testing hardened steel without too much preparation of the surface, it was preferred in the shop and inspection room; the laboratory preferred the slower, but more positive, Brinell method. Since the laboratory and shop used two different methods, two hardness languages came into existence; this created difficulties, because no exact mathematical relationship between them was possible.

During this time Stanley P. Rockwell, who was working as a metallurgist in a large ball-bearing manufacturing plant, was particularly concerned with hardness control of ball races. There was no entirely satisfactory method for controlling the hardness of these and many other hardened steel parts, and as a result of his study and experiments for a means of accurately measuring their hardness, he invented the tester which has become known as the Rockwell hardness tester. This was in 1919. The word "Rockwell" as applied to the tester and also as applied to test blocks has long been registered as a trade mark in the United States and many other countries. The Wilson Mechanical Instrument Co., Inc. of New York City is the manufacturer of the Rockwell hardness tester.

The early model Rockwell tester as built by the inventor is shown in Fig. 23. It consisted of a sturdy, hollow cast frame, together with a plunger which held the testing point at one end; the other end was abutted against a delicate measuring device. A series of levers with knife edges connected this plunger with a weight. By shifting the position of this weight, more or less weight was applied to the testing point at will, to suit testing conditions. This weight, originally called the final weight, was applied and released by a hand lever. An elevating screw with chuck or anvil held the work. An initial pressure was applied by compressing a spring in the head of the machine. The hardness was read

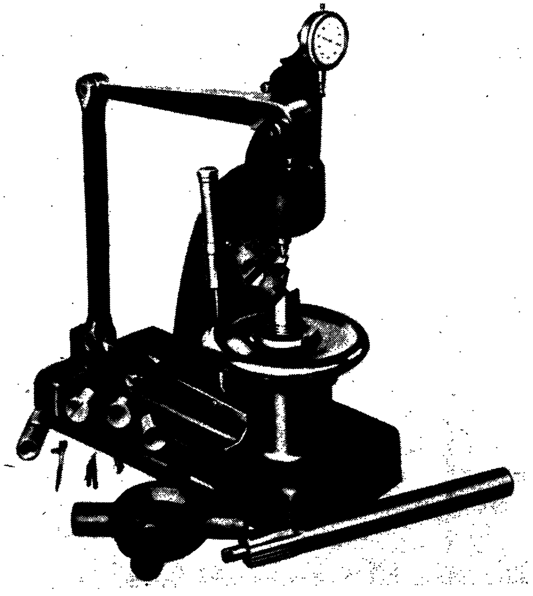

Figure 23. Early model Rockwell tester.

(Courtesy Wilson Mechanical Instrument Co., Inc., New York, N. Y.)

directly as the increment of depth caused by the increment in load as indicated by a measuring device.

In 1920 Charles H. Wilson, then president of the Wilson-Mauelen Company, now the Wilson Mechanical Instrument Co., Inc., visualized the tremendous possibilities of the Rockwell tester for shop testing, as well as the use of the same instrument for laboratory and research work, and took over from the inventor the manufacture and sale of the Rockwell tester. To use the words of Rockwell, it was Wilson who "brought it to the attention of the public, sold it to those who needed it, and thus created business and employment."

Wilson's contribution goes far beyond this. Being an instrument manufacturer and not a metallurgist, he was concerned with building the Rockwell hardness tester into a precision measuring instrument, which would read the same within manufacturing tolerances, even though the quantities involved were of exceedingly small values. Many changes were introduced into the Rockwell tester. The scale, which originally ran from 0 to 100 and had low values for high hardness numbers and high values for soft materials, was reversed so that the values would be in agreement with Brinell and Scleroscope numbers, *i.e.,* high numbers for high hardness values and vice versa. The scale started at 100 and went to 0.

Next, and very important, the loads were standardized. The minor load (previously referred to as initial pressure) was standardized at 10 kg and was carefully controlled. It was recognized early that the minor load application would be responsible for the accuracy of the test, because no testing surface is exactly flat; in other words, it was of as much, if not more, value from a measuring standpoint as from a metallurgical standpoint. When this load was accurately applied there was a fixed zero or starting point. This made the Rockwell test independent of small surface imperfections—"ridging" or "sinking" of impressions—and all tests started from the same position. The need of accuracy of major load, of course, was also appreciated and the major load was applied under control of an oil dash-pot which in no way interfered with its full and correct application.

The original testing point was a hardened steel ball of 1/16-in. diameter. When heat-treated and hardened steels were tested, the ball became flattened. Rockwell's practice was to make a few tests with a new ball and purposely flatten it; thereafter little further permanent deformation took place. After a little use it became apparent that this was not satisfactory. With a load of 100 kg and a flattened ball, small differences in hardness were not being distinguished. Wilson eliminated this difficulty by two changes: increasing the major load for testing hardened steel to 150 kg, and developing a diamond penetrator, known as the Brale * penetrator. After much experimentation he standardized on a diamond cone of 120° angle with a radius of 0.2 mm truly tangent to the cone.

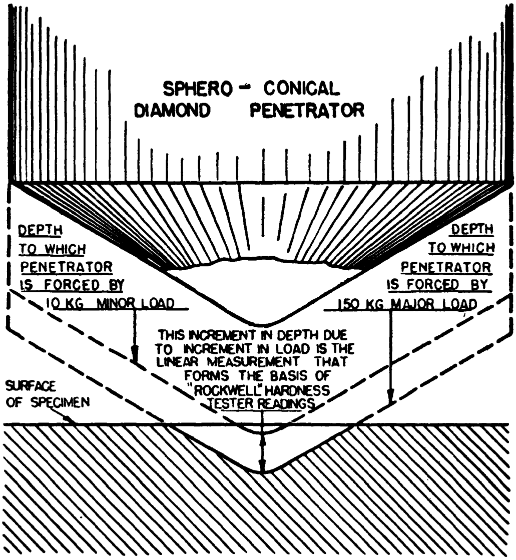

Figure 24. Principle of Rockwell hardness test. (Diamond Brale penetrator illustrated).

This sphero-conical diamond penetrator has four distinct advantages:

(1) It would not deform permanently under testing load because of its material.
(2) It would not penetrate too deep under minor load pressure because of radius.
(3) It would have a long life because of radius.
(4) It would not penetrate too deep in testing sheet metal because of broad angle and radius.

One other factor needs to be explained. Hard steel could be tested with the diamond Brale penetrator and 150-kg major load, and soft steels and brass with the $\frac{1}{16}$-in. ball penetrator (for there was no need to use the diamond on such soft materials) and 100-kg major load. However, this 100-kg load was still so heavy that soft brass gave negative readings which were confusing. Increasing the scale used with the $\frac{1}{16}$-in. ball penetrator 30 numbers, by starting the scale at 130 rather than 100 solved this problem. Thus positive readings for soft brass and good

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* Registered Trade Mark.

sensitivity to hard brass were obtained, because the load remained at 100 kg. To test soft material and to avoid super-sensitivity at low values, a load of 60 kg was introduced.

Having explained in some detail the development of the Rockwell hardness tester, it may be summarized as follows. The Rockwell hardness number is based on the additional depth to which a test point or ball is driven by a heavy load, beyond the depth to which the same penetrator has been driven by a definite light load. A minor load is first applied and quickly thereafter a major load is applied and removed, and the hardness number is automatically indicated on a dial, the minor load still being applied.

Thus a partial recovery in the depth of the indentation due to elasticity of the specimen upon removal of the major load is brought about. More important is the elimination of the deflection of the structural members of the tester, which occurs during application of the major load. The minor load alone is applied when the measurement of the impression is started, and likewise the minor load alone is applied when the hardness number is read from the dial gauge. Deflection of the frame of the tester is thus the same at the start of the test and at the reading. Insofar as recovery of the specimen is concerned, the minor load is applied both when the depth measurement begins and when the reading is made.

The minor load is 10 kg and the major load is 100 kg when the $\frac{1}{16}$-in. diameter steel ball penetrator is used, or 150 kg when the sphero-conical diamond Brale penetrator is used.

The combination of diamond Brale penetrator and 150-kg major load is known as the "C" scale. The "B" scale of the Rockwell tester is the combination of a $\frac{1}{16}$-in. diameter steel ball penetrator and 100-kg load. These are the standard scales.

Fig. 24 shows the principle of the Rockwell test. The principle of increment in depth due to increment in load instead of measurement of total depth or total diameter offers the following two distinct advantages, in addition to freedom from error due to "ridging" or "sinking" of metal at the surface of the specimen:

(1) Readings are more independent of original surface condition of specimens.
(2) Precision testing is possible at rapid rate of test without loss of accuracy.

The units are so chosen that one point of hardness is equal to a depth of only 0.002 mm or 0.00008 in. It is apparent that with such small values the depth-measuring system must be accurate and that loads must be applied properly and with friction reduced to a negligible amount.

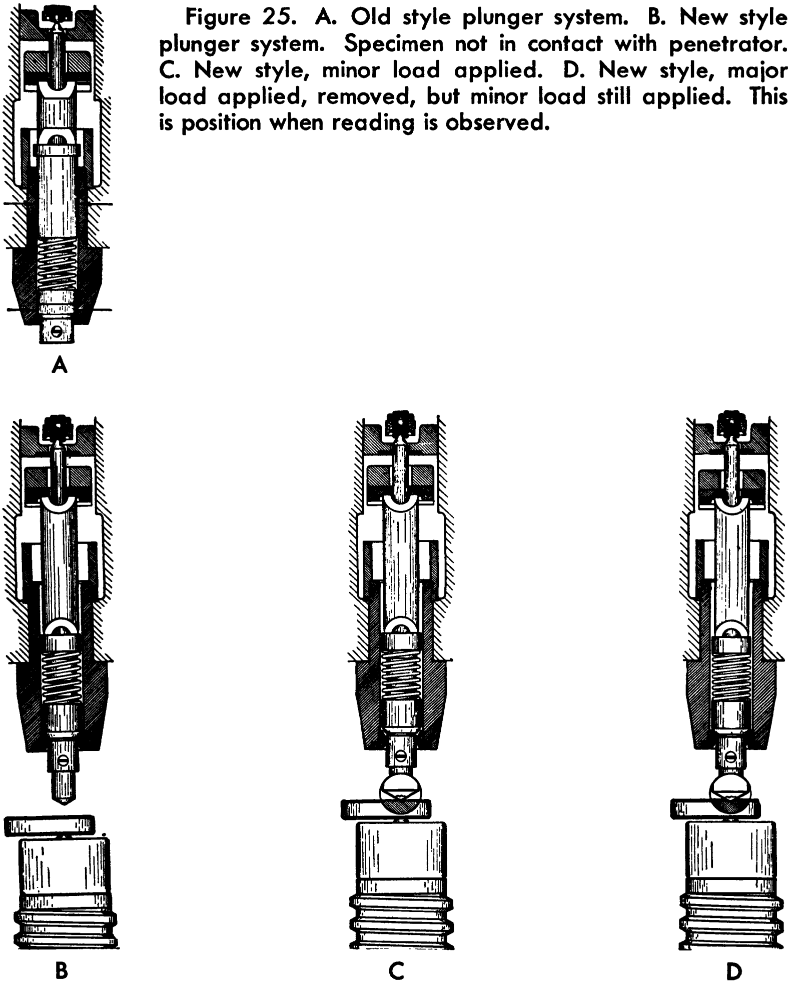


Figure 25. A. Old style plunger system. B. New style plunger system. Specimen not in contact with penetrator. C. New style, minor load applied. D. New style, major load applied, removed, but minor load still applied. This is position when reading is observed.

Apparatus

The Rockwell hardness tester is a machine that measures hardness by the depth of penetration of a test point or ball into a specimen under the definite but arbitrarily fixed conditions, as described above.

The major load is applied by a dead weight loading device originally consisting of a compound lever having a multiplication of about 120. The minor load is applied by compression of a helical spring in the head mechanism of the tester. The loads are transmitted to the test point through a plunger system. In making a test the specimen is placed on an anvil in the elevating screw; by raising this screw with a handwheel, the specimen is pressed against the test point until the minor load is applied. The pointer of the dial gauge is then set at "CO" or "Set" and the major load applied gradually under dash-pot control. After the major load has been fully applied and the pointer on the dial gauge comes to rest, the major load is removed, leaving the minor load applied. The Rockwell number is read from the dial gauge, connected to the plunger system in the head of the tester by means of a lever having 5:1 ratio.

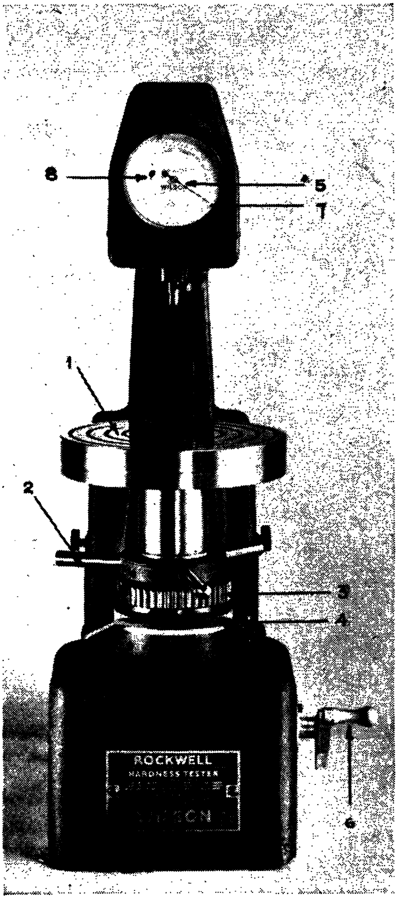


Figure 26. High precision laboratory method, normal operation, using only outer movable scale.

1. **Place specimen securely upon anvil or table.**
2. **Elevate specimen into contact with penetrator and further until small pointer (8) of the indicating guage is nearly vertical and slightly to the right of the dot; then still further until large pointer points vertically upward.**
3. **Turn zero adjuster till the "set" arrow on dial is exactly back of pointer.**
4. **Push depressor bar down to apply major load.**
5. **Watch pointer till it comes to rest.**
6. **Pull crank handle forward, lifting major load, but leaving minor load still applied.**
7. **Read Rockwell Hardness Number.**

(*Courtesy Wilson Mechanical Instrument Co., Inc., New York*)

Two scales are provided on the dial gauge. The outer circle of figures and letters is in black, and all readings with the diamond Brale penetrator are taken on this. The inner circle of figures and letters is in red, and all readings with ball penetrators are taken from these. The zero set point is always the same regardless of which scale is used.

The dial gauge is a 1-millimeter gauge, *i.e.*, one revolution of the large needle equals 1 mm travel of the dial rack. There are 100 divisions to a revolution and as the lever ratio is 5 to 1, each division on the dial represents a depth of 0.002 mm or 0.00008 inch.

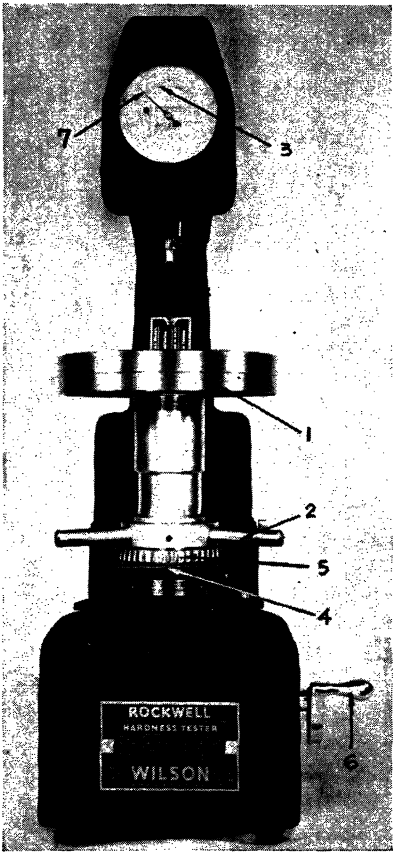


Figure 27. High speed inspection test method, using both movable and "Zerominder" scales.

1. **Place specimen securely upon anvil.**
2. **Elevate specimen into contact with penetrator and further until *small* pointer of the dial gauge is nearly vertical and slightly to the right of the dot; then still further until *long* pointer points *approximately* vertically upward.**
3. **Observe the *exact* position of long pointer on fixed, colored, "Zerominder" scale.**
4. **Tap downward on the depressor bar to apply major load.**
5. **Turn knurled ring (zero adjuster) with thumb till the "set" arrow on dial is in exactly the same position on "Zerominder" scale you observed in Paragraph 3.**
6. **When *long* pointer comes to rest, pull crank handle (6) forward, lifting major load, but leaving minor load still applied.**
7. **Read Rockwell Hardness Number.**

(*Courtesy Wilson Mechanical Instrument Co., Inc., New York*)

Experience with early model testers showed that the design was subject to friction due to wear, dirt, corrosion and drying of the lubricating oil in the link pins and bearings of the lever system. In this model the *plunger rod system used for applying the minor load, contacting the dial* gauge and transmitting the major load pressure to the test point, shown in Fig. 25. The arrows indicate where dirt, grit and dry oi tended to create more friction.

Later design testers have a single-lever load-applying system (ratio either 20 or 25 to 1) eliminating link and pivot pins and using heavy standardized interchangeable weights, thus reducing errors due to friction. In addition to this, further freedom from friction is obtained in a patented frictionless plunger system (Fig. 25). A machine similar to these models is manufactured by Clark Instrument Co., Inc., of Dearborn, Michigan. It is known as the Clark hardness tester.

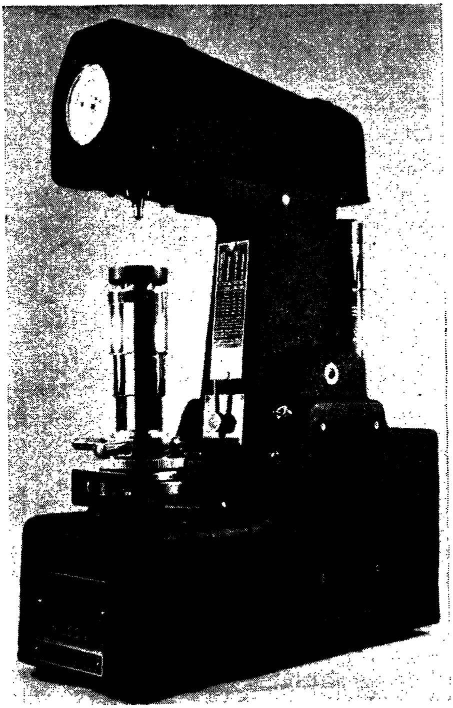


Figure 28. Rockwell motorized tester.

(Courtesy Wilson Mechanical Instrument Co., Inc., New York, N. Y.)

The most modern models of the Rockwell tester have additional advantages. The J model is completely enclosed to keep out dirt and dust, and all operating controls are grouped together in front of the machine so that the operator has no long reaches to make; thus fatigue is reduced and speed increased. A supplementary scale, known as the Zerominder scale, is introduced on the dial, which permits dial zeroizing *during, instead of before, the major load application* (Figs. 26 and 27).

Other models include a motorized machine in which the major load is applied and removed by means of motor and cam arrangement. Two speeds are provided, one in which the cycle of major load operation is ing a larger area of the specimen—an advantage when the material is not of homogeneous structure.

The F scale is used to a considerable extent in testing annealed brass and copper because it is not as sensitive as the B scale in the lower range and also permits testing thin sheets.

The G scale is used for materials in hardness range near B100 where more sensitivity is required than can be obtained in the upper B scale, as in testing beryllium copper, phosphor bronze, etc.

The L, M and R scales are used principally for testing plastics and soft metals, such as lead.

Table 2 gives an approximate idea of the value of the less commonly used scales in terms of the B scale. This table is not to be used as a conversion table. Relations between the B, E, F, G, H, and K scales are shown in the Appendix.

Table 2. Approximate Relation between B, L, M, P, and S Scales of the "Rockwell" Tester

B	L	M	P	S
100	126	123	119	
90	124	120	113	
80	122	116	108	
70	119	112	102	
60	117	108	97	
50	115	105	91	
40	113	101	86	
30	111	97	80	
20	109	93	75	
10	107	90	69	105
0	105	86	63	

The other scales are selected when the particular combination of load and penetrator offers some particular advantage with respect to both the hardness and the thickness of the specimen, as in testing bearing metals, zinc, aluminum and soft copper.

Calculating the Depth of Indentation

When using the C, A and D scales, *i.e.*, those which use the black figures on the dial gauge, the depth of indentation due to increment of major load over minor load is 100 minus dial reading multiplied by 0.002 mm. By formula for black-figured scale, depth of major load indentation over minor load in millimeters equals (100 − reading) × 0.002, or in inches (100 − reading) × 0.00008.

It is more difficult to obtain the depth of indentation of minor load. Fig. 29 shows this in terms of C scale divisions of the dial for the C, A, and D scales. This curve is approximate only, as it is obtained from calculations made from measured diameters of minor load indentation. This calculation assumes the minor load indentation to be made entirely from the spherical part of the diamond Brale penetrator, which may not be the case in testing material as soft as C20 in hardness. Dial divisions multiplied by 0.00008 give minor load depth in inches. A and D scale values must be converted to C scale to use Fig. 29. The total depth of indentation is the sum of minor load depth and depth due to increment of load as measured on the dial.

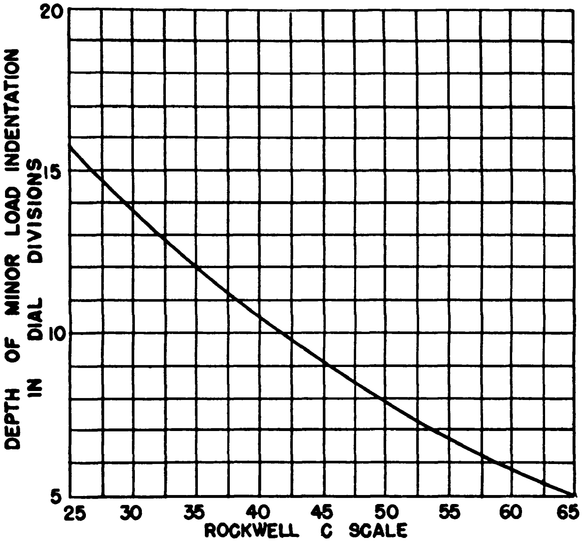


Figure 29. Depth of minor load indentation for Rockwell C, A, and D scales.

In using the red-figured scale on the dial, the depth measured is 130 minus the reading multiplied by the same constants, or by formula for red-figured scale, depth of major load indentation over minor load in millimeters equals (130 − reading) × 0.002, or in inches (130 − reading) × 0.00008.

The curve in Fig. 30 gives minor load depths in B scale dial divisions when using the $\frac{1}{16}$-in. ball penetrator, as in the B, F and G scales. These values are approximate only because of error in reading the diameters of indentation, which are small values. Dial divisions multiplied by 0.00008 give minor load depth in inches. F and G scale values must be converted to B scale to use Fig. 30. From these values and the formula the total depth of indentation may be obtained.

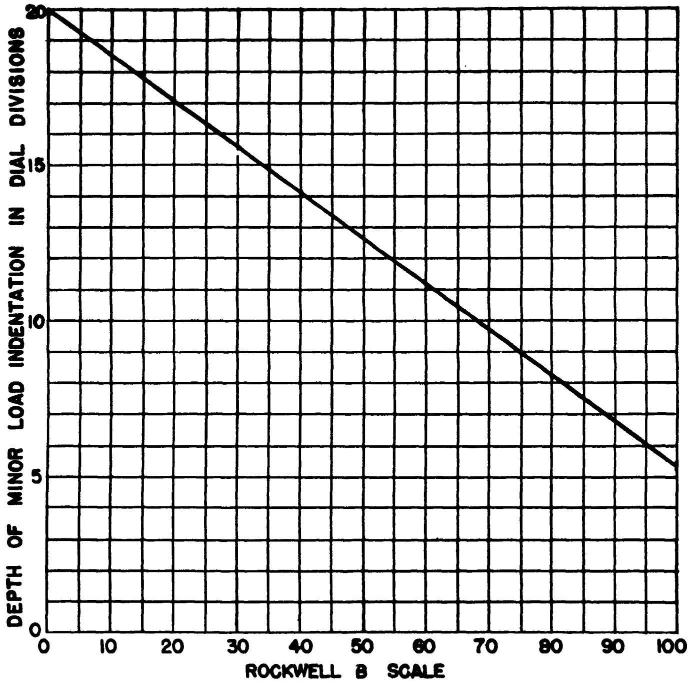


Figure 30. Depth of minor load indentation for Rockwell B, F, and G scales.

Standardization of the Test

The Rockwell hardness number is not capable of definition in terms of the fundamental units of length, mass and time. Although the loads may be defined and value of each unit of depth also defined, such perplexing problems as shape of penetrator, accuracy of loads, accuracy of depth-measuring dial gauge, rigidity of machine, method of applying loads, lubrication, alignment, and such factors as dirt or other particles between working surfaces, prevent translating the definition into practical specifications for a tester.

The A.S.T.M. specifications, especially E 18–42 and the B.S.I. #891: 1940, are in reality directions as to how the hardness tester should be used, but they give no definition of Rockwell hardness.

Granted that considerable experimentation with accurately-shaped penetrators, application of loads under a definite schedule and as accurately as possible, measurement of indentation depth with nearly perfect gauges, etc., might result in establishing a set of tolerances as to the size and shape of the indenting tool, the variations in minor and major loads and depth-measuring system—even so, there is no assurance that the number so obtained would be the same as the present Rockwell number. As the Rockwell hardness tester measures the depth of the indentation by the movement of the plunger rod, any working surfaces which are not in perfect alignment or bearing surfaces which are not parallel will probably give incorrect readings—usually low ones.

Thus a machine with perfect loads, perfect penetrators and a perfect depth-measuring system might give erroneous readings if the surface between the shoulder of the penetrator and face of the plunger rod was dirty or nicked. Poor seating of an anvil on an elevating screw due to dirt, grit, burrs, or corrosion, as well as inexact fit of the capstan handwheel on the surface on which it rests, will likewise cause inaccuracies.

There is no such thing as a perfect diamond Brale penetrator. A really true sphere cannot be generated at the apex of a cone because of the structure of a diamond and of the method which must necessarily be used to grind the sphere. Because of the crystal planes in a diamond, a true diamond cone cannot be produced. When examined under magnification by optical projection, the image varies as the penetrator is rotated. Table 3 gives values of five indenters examined by the National Bureau of Standards.

Table 3. Data on Diamond Brale Penetrators' Angles

Manufacturer's No.	Position[1]	Angle of Cone °	Angle of Cone ′
26–1886	1	120	0
	2	120	6
	3	120	18
26–1832	1	119	55
	2	119	51
	3	120	3
26–15	1	120	1
	2	120	1
	3	120	18
29–1893	1	119	41
	2	119	32
	3	119	53
26–224	1	120	25
	2	120	4
	3	119	48

[1] The Brale was turned into position 2 from position 1 by rotating it 60° about its axis. An additional 60° rotation brought it into position 3.

The question naturally arises as to how the manufacturer of the Rockwell hardness tester is able to standardize the instrument and the penetrators and give assurance that the standards do not fluctuate. This is accomplished by means of careful work of standardization of gauges, lever lengths, loads, and the large number of factors that must be watched and controlled to maintain real consistency. Major loads must be carefully controlled; minor loads must also be controlled, though not to the same limit of accuracy.

The Rockwell test is quite different from the Brinell method, which is a ball, load and diameter specification; the Rockwell is far more complex and is to a large extent empirical because of the arbitrary design used by the manufacturer.

More than 35,000 Rockwell testers have been built on this basis, and many thousand specifications as well as invaluable data have been gathered from extensive research using the Rockwell number; hence it must be recognized that the Rockwell tester is *de facto* in wide use. Should it be desired to change the definition in an attempt to relate the number to fundamentals of length, mass and time, the result in all probability would not give the same number as the Rockwell number used for the last 20 years, and thus all hardness standards and control of manufacturing processes would be upset.

The present diamond Brale penetrator standards are based on a large number of commercially perfect penetrators. These, when used in a group of carefully built Rockwell testers, with correct loads and accurate depth-measuring systems, if properly assembled and with working surfaces in proper relations, are the standards for the C, A and D scales. The results obtained with such machines and with such penetrators on uniform test blocks, correlated with tests made over a period of 20 years, provide assurance against anything more than normal fluctuation of standards.

The ball penetrator standards are maintained in the same manner. The balls are of hardened steel which is carefully controlled and of correct nominal diameter within ± 0.0001 in.

It is a simple matter to check the accuracy of a Rockwell hardness tester. First one should make sure that the major load is being applied at the proper speed. The dash-pot should be so adjusted that the operating handle completes its travel in 5 seconds with no specimen in the machine, using the 100-kg major load. Next check the machine using Rockwell test blocks. A block near (preferably within ± 5 numbers) the hardness of the material being tested should be used; or if the tester is being checked throughout a scale, blocks of upper, lower and intermediate hardness of the particular scale should be used. Five impressions are generally made and averaged, and if the average agrees with the values marked on the block, the machine is considered satisfactory. Only one side of the test block should be used and the block should not be reground or filed when filled.

If two users want their testers to agree more closely than the tolerances on the test blocks, they must apply a correction factor determined from the average of many readings on uniform material for the particular number on the scale on which they are working.

The following information taken from the manufacturer's statement with each block is very important: "The homogeneity of one side of block, determined by six tests is within limits engraved on edge of block. As no absolute standards of hardness are available and no commercial material is truly homogeneous in hardness, this block is supplied as a helpful guide, not as an absolute standard.

"Furthermore, our machine on which the blocks are tested may have some error, for its own calibration is not possible closer than plus or minus half a point for hard blocks and proportionately less exact for deeper penetrations." If correct readings are not obtained when the machine is checked on test blocks the directions supplied by the manufacturer should be consulted.

The question is often raised as to when the major load should be removed when testing soft materials which flow under the applied load. The manufacturer's instructions state that it should be removed when the dial pointer comes to rest. The A.S.T.M. E 18–42 states it should be left on until the major load is completely applied. This is determined (1) when the pointer suddenly slows down or (2) when the weight arm is completely free from the control of the dash-pot. It continues, "the operating handle shall be immediately brought gently back to its latched position; this shall be accomplished within 2 seconds after the major load has been completely applied."

When these specifications were established they were all in accord for the majority of tests, except for testing materials like zinc and plastics which flowed considerably. Under such conditions, a time factor was used; this was set arbitrarily to suit the conditions of test. However, the use of deep-drawing automotive steels, about Rockwell B40, which are controlled for hardness by the Rockwell tester and which flow to a definite degree under major load of 100 kg, calls for reexamining this question. If the operator waits for the needle to come to rest, the test is slowed up considerably.

If condition (1) of A.S.T.M. E 18–42 is followed, a personal element is introduced into the test. Condition (2) of E 18–42 cannot be observed in the J model tester. Two alternatives are available. One would be the use of the F scale, which would reduce the flow so that it would become negligible. This would not be out of line, for good sensitivity would be obtained on the F scale for such hardness values. Since brass is usually tested on the B scale for rolled tempers and on the F scale for the annealed condition, no new precedent would be established in testing soft sheet steels on the F scale and harder sheet steels on the B scale. The second alternative would be for supplier and user, through some authoritative body, to establish arbitrarily the duration of application of the major load. It should not be done for testing generally on the B scale, because materials which do not flow under load are not affected. The question arises as to why one material should be made harder than another on a Rockwell scale by arbitrarily applying a time factor which *is necessary only for a few special cases when the operator cannot wait until equilibrium is reached.* The Rockwell test is a static test and the true Rockwell number results when conditions of equilibrium are approached.

The Rockwell testing of sheet materials and round surfaces will be discussed in later chapters and will be mentioned here only in passing.

If the thickness of the piece being tested is such that a mark on the reverse side shows the effect of the load, the Rockwell hardness number may be in error. All Rockwell tests must be made on a single thickness of the material, because in testing metals, the use of additional thickness of the same material does not give the same result as a solid piece of the same thickness. This is due to flow of the material on the surfaces between the various pieces.

For testing cylindrical pieces of less than ½-in. radius, the radius of the curved work should be specified if the readings are to be related to tests on flat surfaces.

Rockwell tests should not be made too close to an edge; the B.S.I. #891:1940 specifies that the center of the impression shall be not less than two and one half times the diameter from any edge of the specimen. The same distance is specified in making a test near any other impression. Experience has shown that this distance is the very minimum which should be observed.

The effect of temperature of the specimen and of the machine has been investigated, and the results are shown in Figs. 31, 32, and 33. The first set of curves shows the variation in Rockwell B and C scale numbers as the specimen temperature is varied over a range which might be encountered in practice, the instrument temperature being constant. Fig. 33 shows the variations obtained with the specimen temperature held constant and the machine temperature varied. The change observed was of small order and was practically negligible for change in tester temperature. It should be noted, however, that these curves were obtained from limited data and are offered only as a guide and for comparison with later results, should the matter be investigated further.

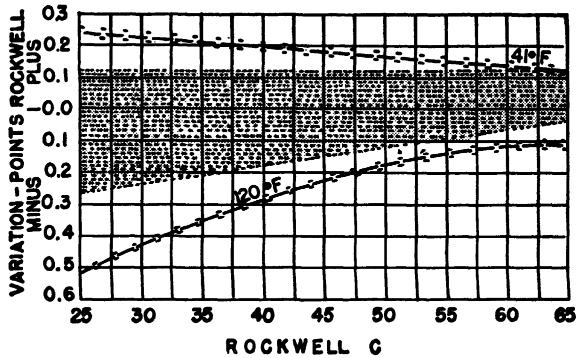


Figure 31. Tester temperature constant 70° F. (*Shaded areas represent expected variation in C scale at normal temperatures. Special lines represent specimen hardness at modified temperatures.*)

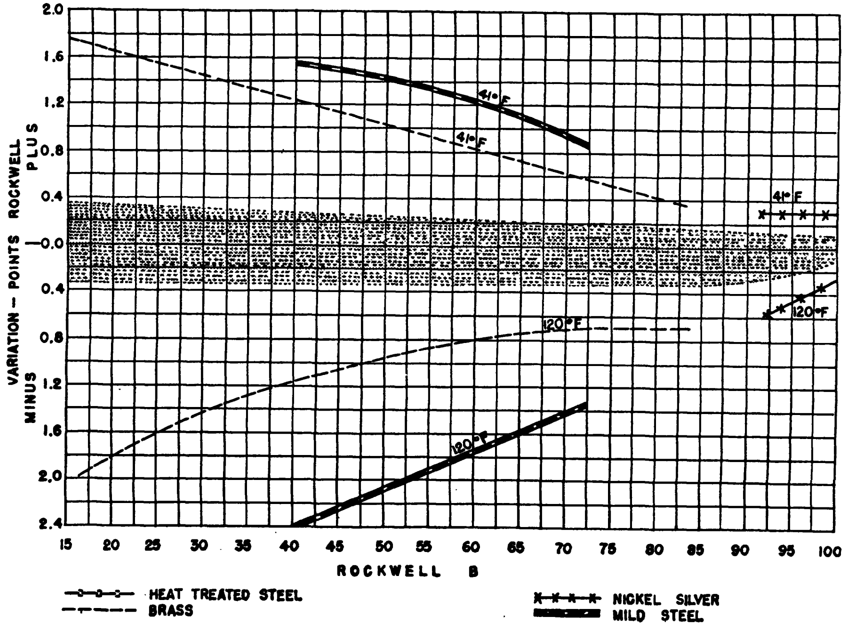
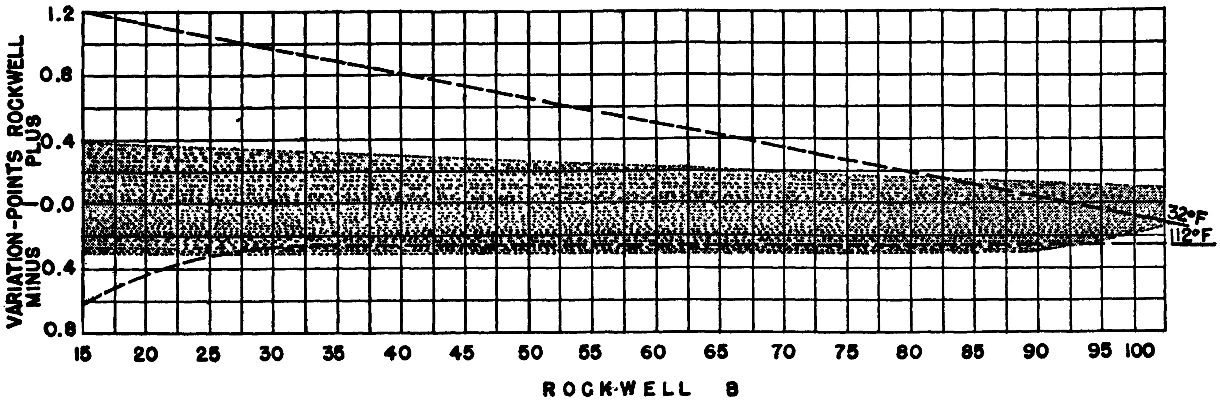


Figure 32. Tester temperature constant 70° F. (*Shaded areas represent expected variation in B scale at normal temperatures. Special lines represent specimen hardness at modified temperatures.*)



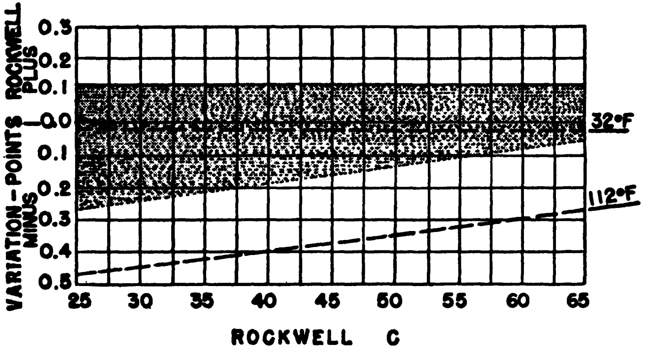


Figure 33. Material temperature constant 70° F. (*Shaded areas represent expected variation at normal temperatures. Broken lines represent machine performance at modified temperatures.*)

Support for the Test Specimen

It is a fundamental requirement of the Rockwell test that the surface being tested be approximately normal to the penetrator and that the piece being tested shall not move or slip in the slightest degree as the major load is applied. As the depth of indentation is measured by the movement of the plunger rod holding the test point, any slipping or moving of the piece will be followed by the plunger rod and the motion transferred to the dial gauge, thus causing an error to be introduced into the test. As one point of hardness represents a depth of only 0.00008 in., a movement of only 0.001 in. could cause an error of over 10 Rockwell numbers. The support itself must be of sufficient rigidity to prevent its permanent deformation in use.

Sheet metal, small pieces or pieces which do not have flat undersurfaces are tested on an anvil having a small elevated flat bearing surface. Pieces that are not flat should have the convex side down on the bearing surface. Fig. 34 shows a complete set of standard anvils.

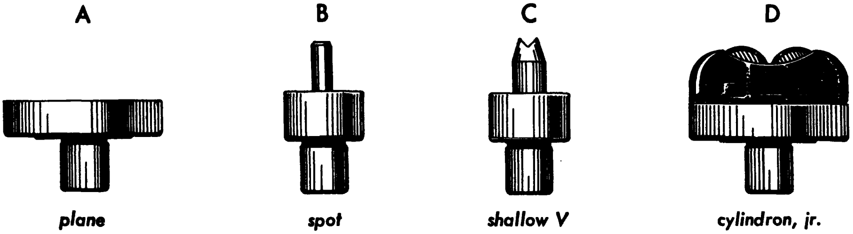
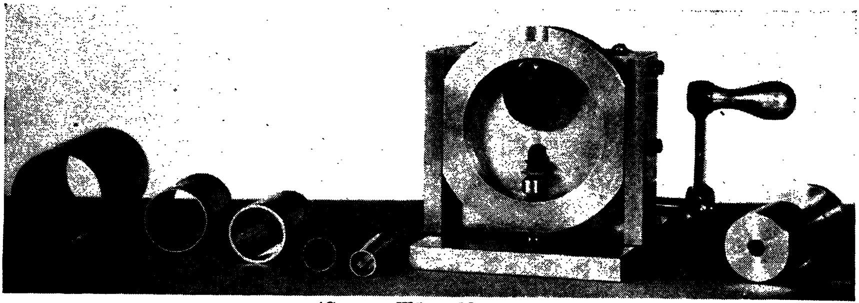


Figure 34. Set of standard anvils for Rockwell tester.

An anvil with a large flat surface should be used for supporting flat-bottom pieces of heavy section. Anvils having a surface greater than about 3 inches in diameter should be attached to the elevating screw by a threaded section rather than inserted in the anvil hole in the elevating screw.

Round work should be supported in a hardened V anvil or in a Cylindron anvil, which consists of hardened parallel twin cylinders. When testing small rounds, it is essential that the center of the V be aligned with the center of the test point and that the piece be straight.

Tubes and hollow pieces must be supported by a mandrel to insure their rigidity under testing loads. Any permanent deformation under application of major load will introduce an error in readings. Fig. 35 shows one form of fixture for supporting and clamping tubing while being tested. This fixture is fastened to the table on the elevating screw of the tester.



(*Courtesy Wilson Mechanical Instrument Co., Inc., New York, N. Y.*)

Figure 35. Tube clamp fixture.

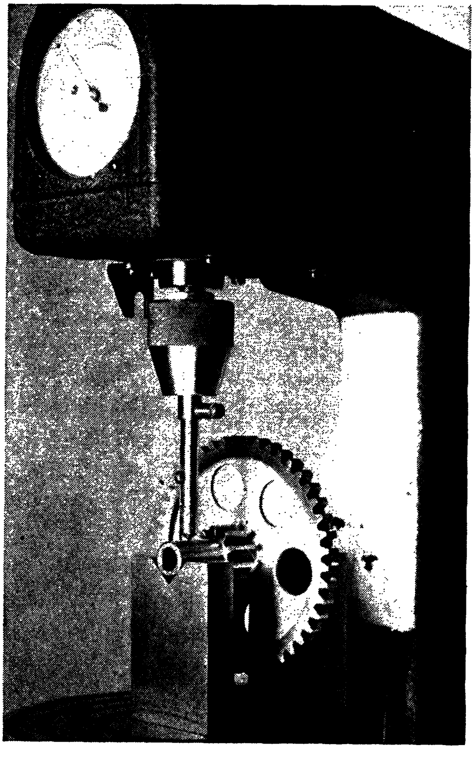


Figure 36. Rockwell testing of irregular shaped parts.

(*Courtesy Pratt & Whitney Aircraft, East Hartford, Conn.*)

An idea of what is required and what may be accomplished in using special fixtures and special diamond Brale penetrators may be obtained from the series of photographs in Figs. 36 to 43. These are reproduced through the courtesy of Pratt & Whitney Aircraft Co. of East Hartford, Conn.

In designing special fixtures it is advantageous to allow their use in supporting several parts. Innumerable fixtures and anvils have been designed, and those illustrated are only to show what may be done. It would be impossible to illustrate all the special anvils used in even one plant.

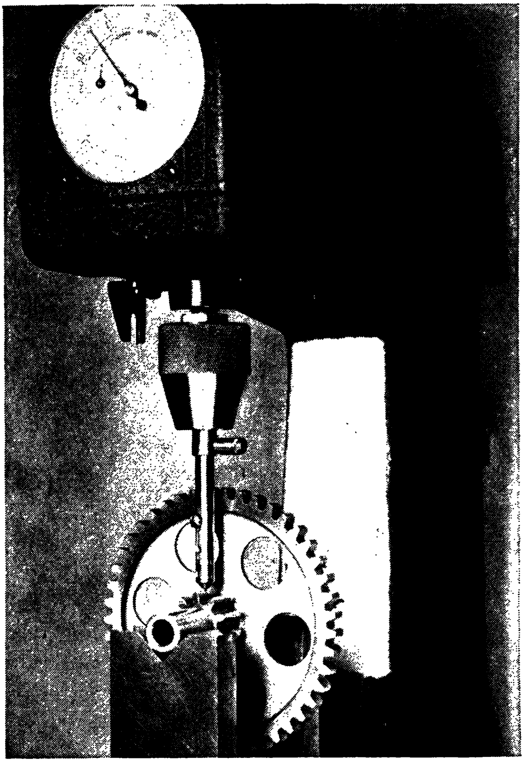


Figure 37. Rockwell testing of irregular shaped parts.

(Courtesy Pratt & Whitney Aircraft, East Hartford, Conn.)

Under some conditions, as, for example, in testing gears on the face of a tooth, it may be necessary to use a specially designed penetrator in order to locate the indentation in the desired position.

Fig. 36 illustrates the use of a double V block to check core hardness on the O.D. of the shaft. Note the use of an extension with the penetrator. The use of the same fixture is illustrated in Fig. 37 for checking the

O.D. of the pinion. By removing the extension the hardness on the O.D. of the gear may be checked.

Fig. 38 shows an adjustable fixture, designed to hold gears in a position to check the hardness of gear teeth on the face of a tooth. The two holding blocks can be set at any position and the two rolls are held on the blocks by clamps, allowing the use of various size rolls.

An elaborate fixture for holding a zerol gear is shown in Fig. 39. Fig. 40 illustrates a holding fixture for a bevel pinion with a straight tooth, the test being made on the tooth flank. Figs. 41 and 42 illustrate fixtures for holding bevel gears. An example of how a cam may be held for checking the hardness on the lobe is shown in Fig. 43.

Auxiliary support is necessary for testing long pieces with so much overhang that they are not firmly seated by the minor load. They may be supported by an adjustable jack or by an arm attached to the elevating screw. Any attachment to the elevating screw should be counterbalanced. Such arrangements are shown in Figs. 44 and 45.

Irregularly shaped pieces which cannot be balanced on a fixture may be clamped in a vise-like manner provided—and this is important—that in clamping the piece under test, it is not stressed to change its physical properties and that in attaching the clamp to the Rockwell tester it does not distort the frame of the tester.

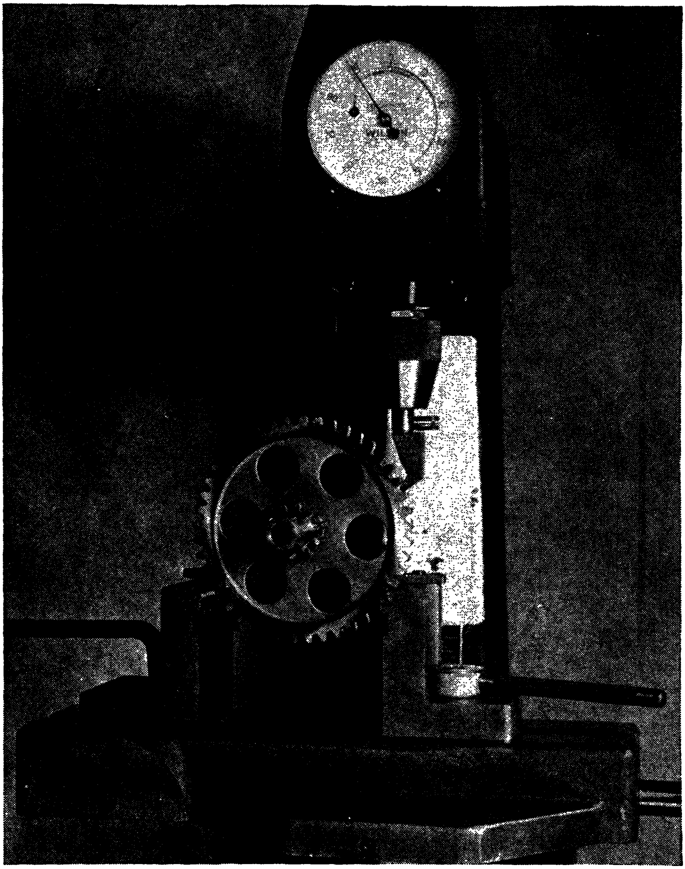
Tapered surfaces up to about 5° (easily observed by the operator) will not be in error provided the piece does not slip as the major load is applied.

Preparation of the Surface

The surface being tested need not be polished but should be smooth, clean, dry and free from scale. This applies also to the surface in contact with the supporting anvil. The surface under test should be representative of the material and not be carburized, decarburized, or affected by grinding or filing, unless the test is being made to determine such characteristics. Deep tool marks and rough grinding may cause incorrect readings, as they afford unequal support to the penetrator.

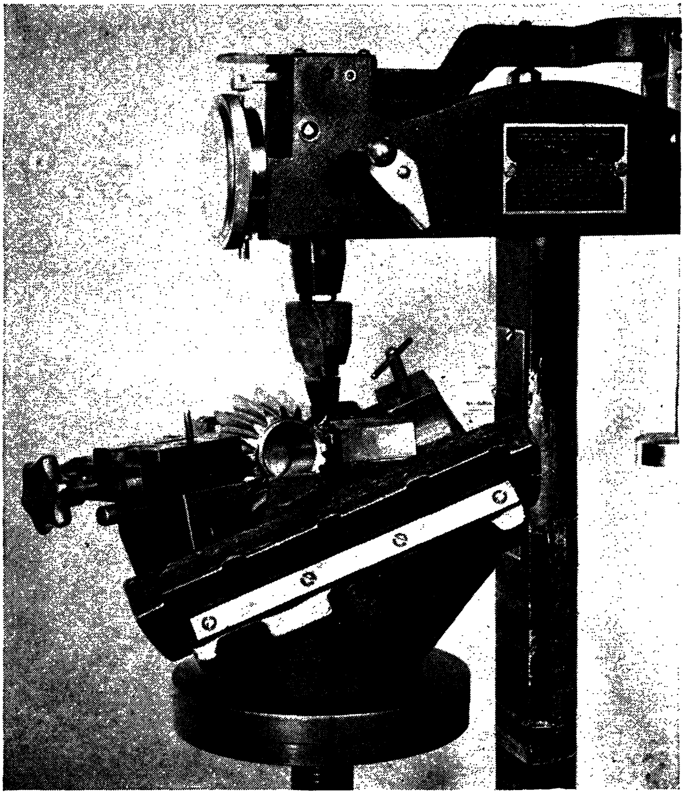
Internal Testing

Internal surfaces of small cylindrical parts may be tested with a gooseneck adapter as shown in Fig. 46. It is attached to the plunger rod like a penetrator, and its weight is such that it does not affect the accuracy of the reading. It will make a test about 3/8 in. from the end of a tube and tubes from 1 in. to about 2¼ in. may be tested. Fig. 46 shows the use of such an adapter for testing the hardness at a spring recess in a plate used in a spring drive.



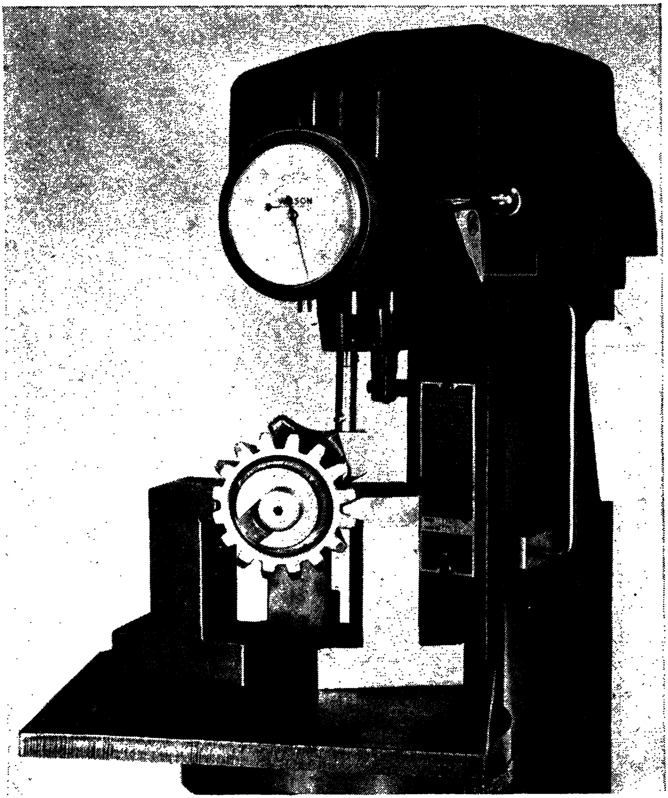
(Courtesy Pratt & Whitney Aircraft, East Hartford, Conn.)

Figure 38. Rockwell testing of irregular shaped parts.



(*Courtesy Pratt & Whitney Aircraft, East Hartford, Conn.*)

Figure 39. Rockwell testing of irregular shaped parts.



(*Courtesy Pratt & Whitney Aircraft, East Hartford, Conn.*)

Figure 40. Rockwell testing of irregular shaped parts.

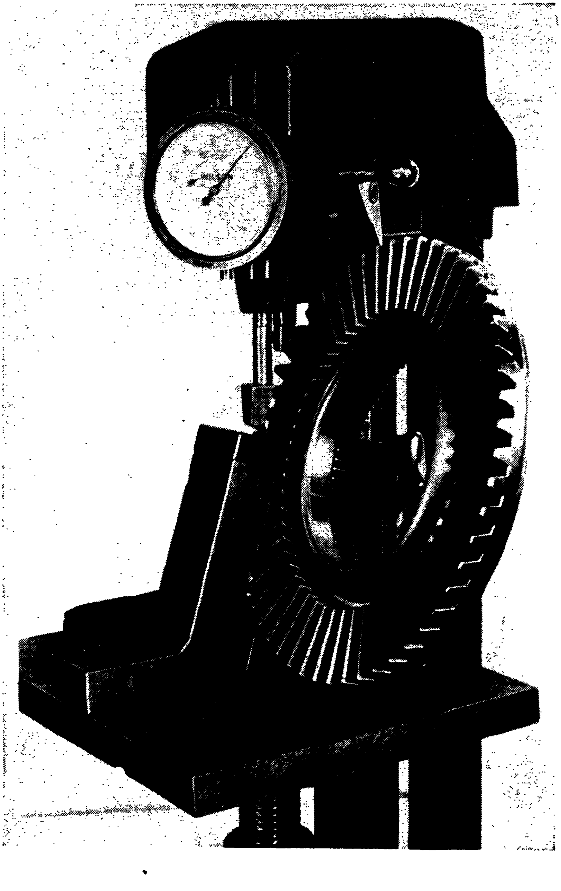


Figure 41. Rockwell testing of irregular shaped parts.

(*Courtesy Pratt & Whitney Aircraft, East Hartford, Conn.*)

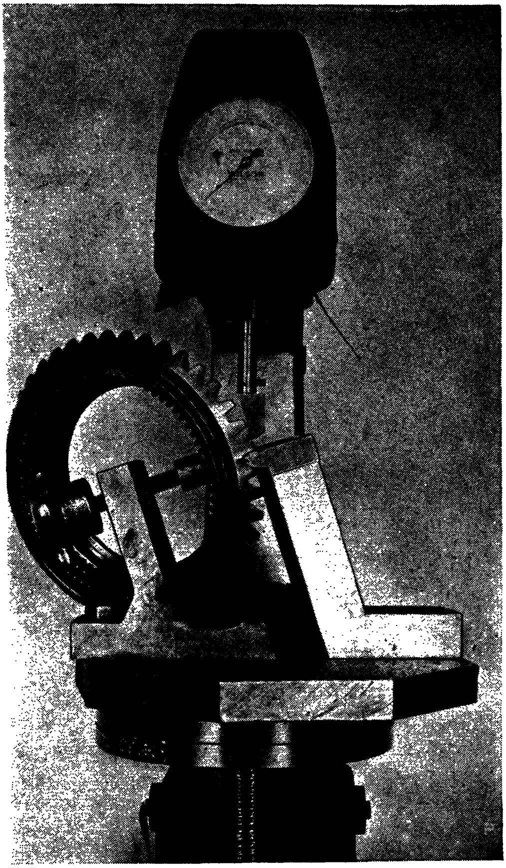


Figure 42. Rockwell testing of irregular shaped parts.

(Courtesy Pratt & Whitney Aircraft, East Hartford, Conn.)

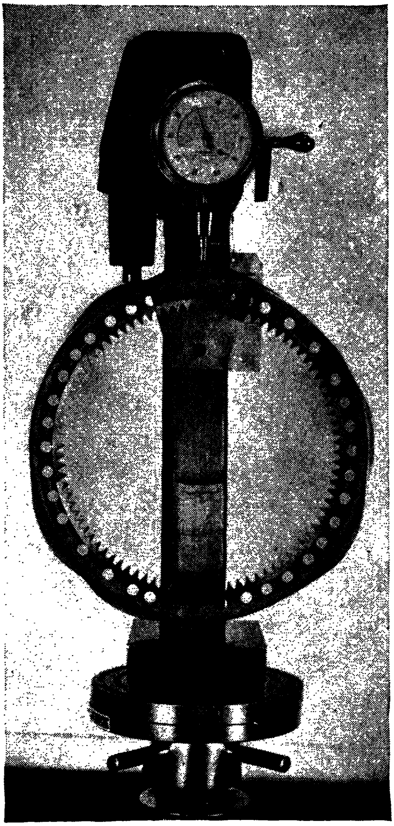
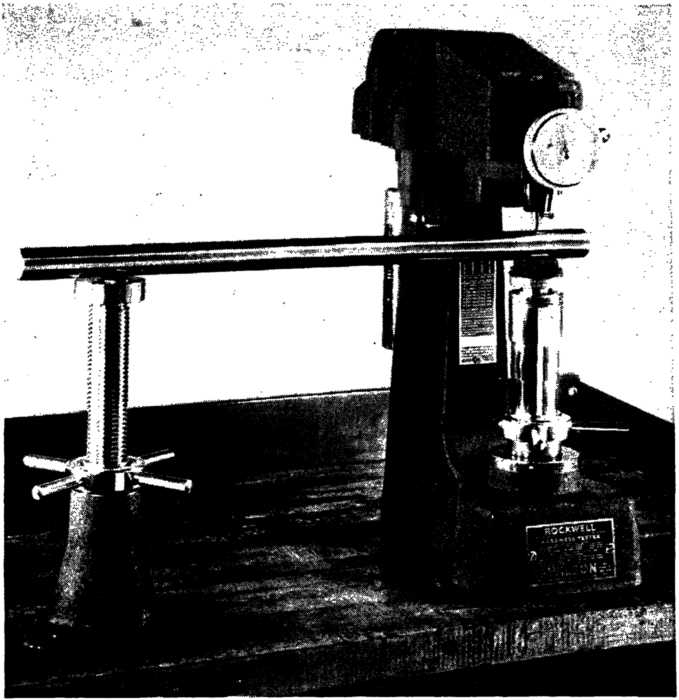


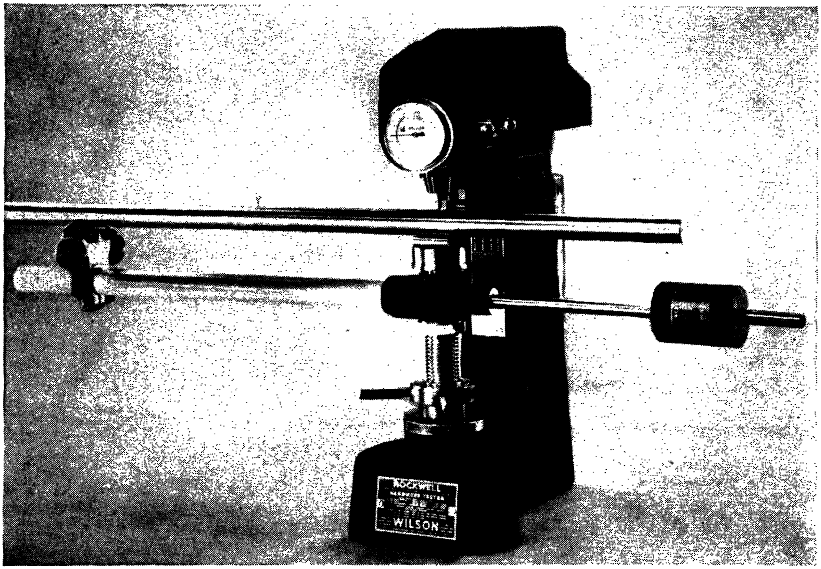
Figure 43. Rockwell testing of irregular shaped parts.

(Courtesy Pratt & Whitney Aircraft, East Hartford, Conn.)



(*Courtesy Wilson Mechanical Instrument Co., Inc., New York, N. Y.*)

Figure 44. Adjustable jack rest.



(*Courtesy Wilson Mechanical Instrument Co., Inc., New York, N. Y.*)

Figure 45. Vari-rest work support.

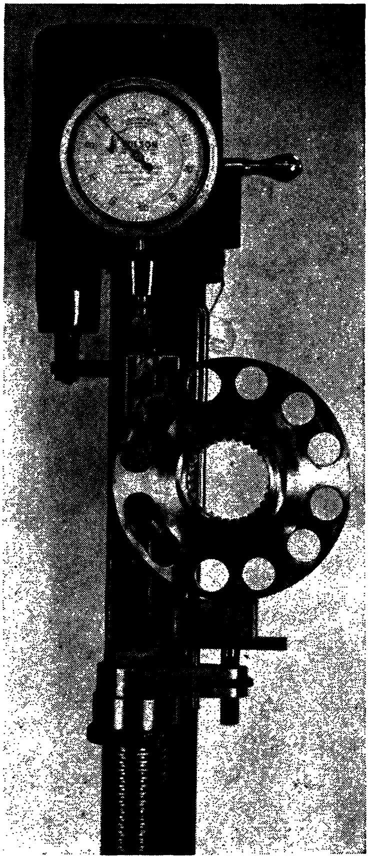


Figure 46. Testing hardness in recess of a drive plate. Note use of small gooseneck adapter.

(Courtesy of Pratt & Whitney Aircraft, East Hartford, Conn.)

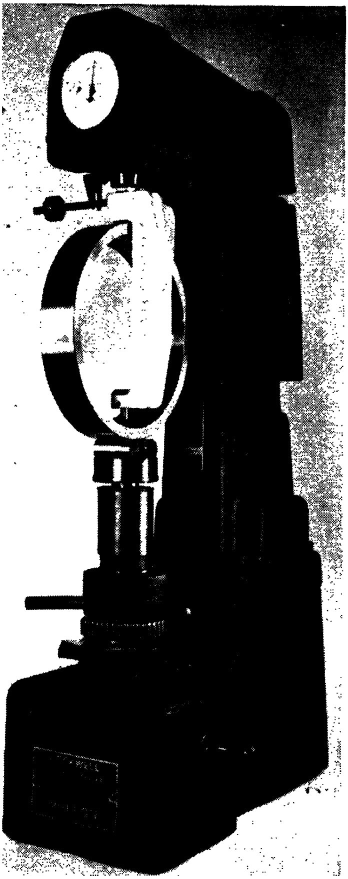


Figure 47. Semi-special Rockwell tester with long gooseneck adapter for internal testing.

(Courtesy of Wilson Mechanical Instrument Co., Inc., New York, N. Y.)

If larger tubes or rings are to be tested, a gooseneck extension must be designed of such rigidity that its weight would not introduce errors in the readings, because a minor load greater than 10 kg would be applied and the major load be increased (Fig. 47). It is possible to compensate for this additional load in building the Rockwell tester; the gooseneck is properly counterbalanced and of sufficient strength not to deform permanently under testing load. It is held in proper alignment by an orientation device. Such a gooseneck is attached to the plunger rod by a tapered section, as it is too heavy to be inserted in an ordinary plunger rod designed to hold only a small penetrator. Gooseneck extensions are built for testing up to about 2 in. from the end of a cylinder, which may be several inches in diameter. Large external surfaces may be tested by removing the gooseneck extension and using in its place a compensator of like weight (Fig. 48). Deep bowl-like pieces and flat surfaces adjacent to a shoulder may be tested by a straight extension. These are satisfactory up to 4 in. in length and must be designed so that

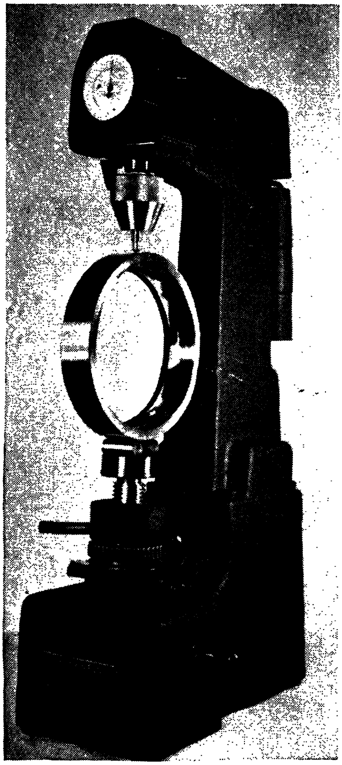
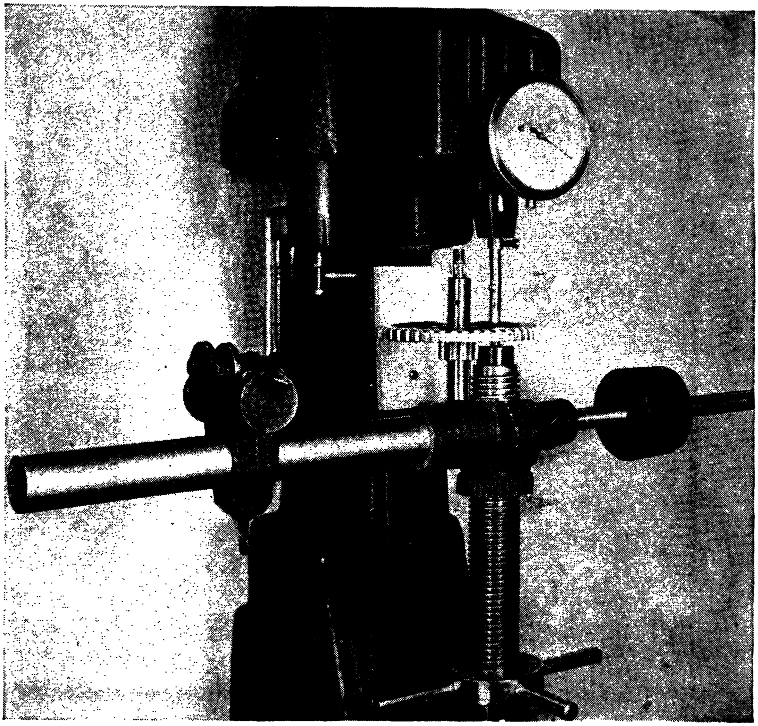


Figure 48. Semi-special tester with compensator in position.

(Courtesy Wilson Mechanical Instrument Co., Inc., New York, N. Y.)

they are not of sufficient mass to require compensation of the loads (Fig. 49).

When it is necessary to test cylinders to a depth of 4 to 5 in., a special internal machine may be required. Such a tester is used for testing cylinders and liners and is illustrated in Fig. 50. They are not as accurate or sensitive as the standard machines because of friction in the head parts of the machine resulting from being cramped into such a small space. In the absence of any better method of testing such surfaces, they generally suffice for production control. Cylinders of 3¼ in. diameter or larger may be tested.



(Courtesy Pratt & Whitney Aircraft, East Hartford, Conn.)

Figure 49. Straight extension used in Rockwell tester.

Large Pieces

Large, heavy work which cannot be tested in the ordinary Rockwell machine because of its size may be tested in a special unit illustrated in Fig. 51. Such parts as large bearing frames and races, machine tool frames, large locomotive gears, steel rolls, armor-piercing projectiles,

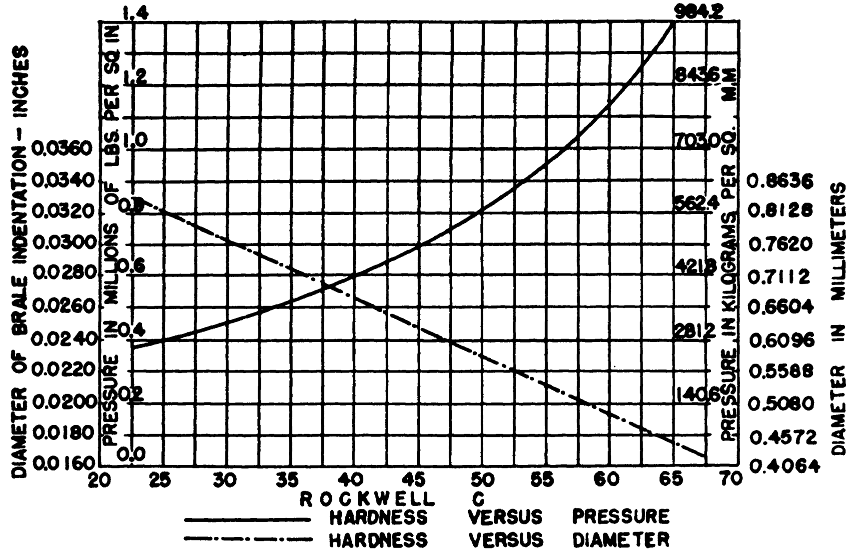


Figure 52. Unit pressure with Rockwell C scale.

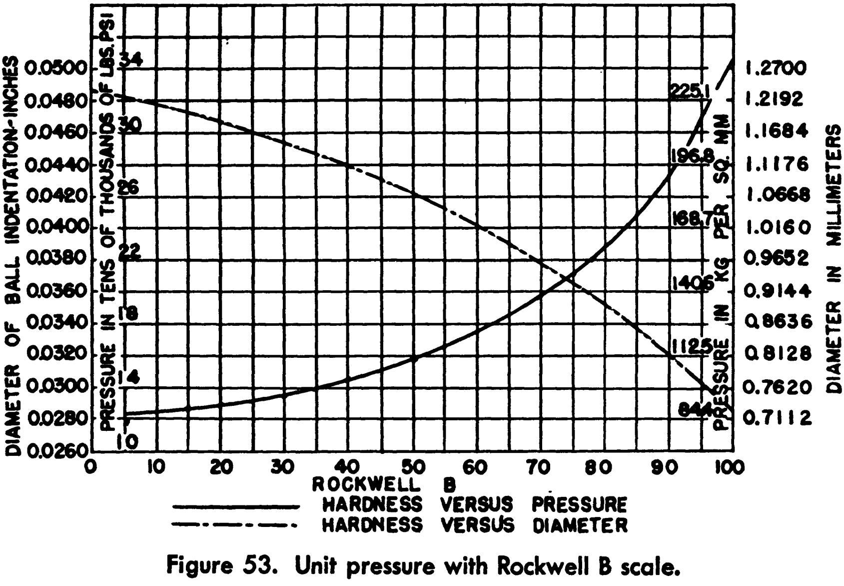


Figure 53. Unit pressure with Rockwell B scale.

The same relation is shown in Fig. 53 for B scale values. These values are of general interest and emphasize the tremendous stress setup in the diamond penetrators. Meyer's analysis has been applied to impressions made with the 1/16-in. ball penetrator on various materials. This work was done by measuring the diameter of the indentation after completion of the Rockwell test and determining the Meyer "n" value. This may be used to study the work-hardening capacity of materials.

R. L. Peek and W. E. Ingerson[1] made an analysis of the Rockwell hardness test by studying results of different loads (60, 100 and 150 kg) and balls of diameter 1/16, 1/8 and 1/4 in.; they determined a relation from the increment of depth of indentation from minor to major load which compared favorably with Meyer's analysis. They showed that when $\frac{h}{D}$ was of small value, *i.e.*, less the 0.1, the relation between depth of indentation and load could be expressed by the formula:

$$\frac{h}{D} = \frac{C(W - W_0)^{\frac{1}{m}}}{SD^2}$$

where

h = depth of indentation from minor to major load in centimeters
D = diameter of ball in centimeters
W = major load in kg
W_0 = minor load in kg
S = constant of material having dimensions of a stress
C and m = dimensionless constants

The law holds for homogeneous samples of brass, aluminum, mild steel, nickel, silver and phosphor bronze.

When $\frac{W-W_0}{D_2}$ is plotted in logarithmic scale against $\frac{h}{D}$ in logarithmic scale, in the same manner as explained under Meyer's analysis, a straight line relation will result. This is a simple procedure, for W, W_0 and D are known and h is determined from the dial gauge. For readings using the B or red-figured scale, h is simply the difference between 130 and the dial reading multiplied by 2×10^4 to obtain values in centimeters or $h = (130 - \text{reading})\ 2 \times 10^{-4}$.

The limited amount of work which has been done along this line indicates that m is a measure of strain or work-hardening and for hardened samples $m = 1$. It appears that $m = 1$ bears similarity to $n = 2$ in the Meyer analysis. The quantity C is a function of the work-hardening properties of the material. If S, which is a constant of the material and has stress dimensions, is taken as the tensile strength of the material, m and C may be computed for a number of different materials.

It has been shown that within the limits of the materials studied, for thicknesses greater than 0.040 in., that, taking S as the tensile strength in kg/sq cm, C lies between 0.075 and 0.085. This formula, therefore,

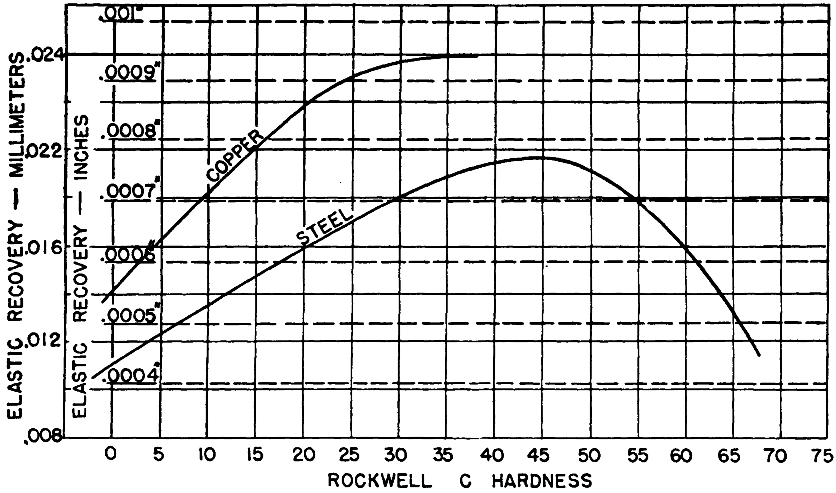


Figure 54. Elastic recovery of work under diamond Brale penetrator.

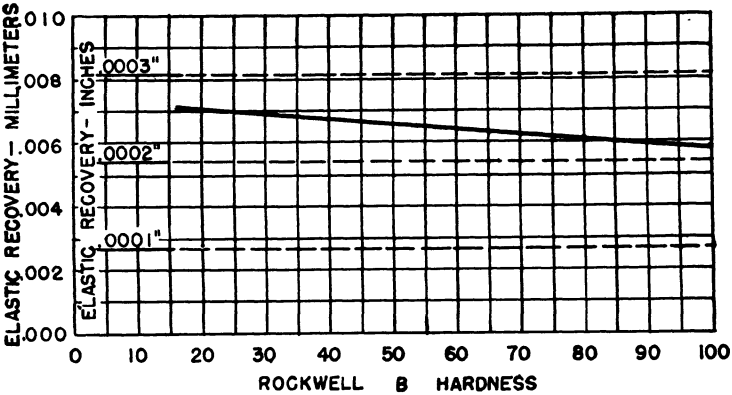


Figure 55. Elastic recovery of work under 1/16 inch diameter steel ball penetrator.

might be developed in usefulness in setting the limits on hardness readings in specifications for control of tensile strength from a few Rockwell hardness readings, a graph for determination of m which is the slope of the line, and use of values of C determined experimentally for different materials. This work may also be used for determining variations in hardness with depth of material, for failure of a point to lie on a common curve indicates variations in hardness with depth within the limits of the thickness of the materials investigated.

The elastic deformation of the ball penetrator is considerable in the Rockwell test, but the Brale penetrator deforms little elastically under load because it is made of diamond. Elastic recovery or spring-back of the metal being tested upon release of major to minor load has been studied; Figs. 54 and 55 from the work of Scott and Gray, of the Westinghouse Electric and Mfg. Co., give an idea of the amount of elastic recovery. It will be noticed that the relation between Rockwell hardness and elastic modulus of the test sample affects the magnitude of the recovery with the diamond Brale penetrator, but with the B scale there is no appreciable effect on the amount of recovery with change in modulus. This is explained as being due to lower stresses and more equitable stress distribution with the ball than with the diamond cone.

The greatest amount of recovery in steel being at C45, about 20 per cent of the impression depth has been explained as possibly representing the maximum toughness of quenched and tempered steel. This work is of value in studying conversion relationships.

The short reference to theoretical studies made of the Rockwell test is presented to show a little of what has been accomplished up to now in this direction, which may later be useful for many purposes.

Reference

1. Peek, R. L., Jr., and Ingerson, W. E., "Analysis of Rockwell Hardness Data," *Proc. Am. Soc. Testing Materials,* 39 (1939).

handle has been tripped for it to complete its travel with the 30-kg load in place and no work in the tester.

The Rockwell superficial hardness tester is available in both hand-operated and motorized models. The operating characteristics of these models are the same as explained for the normal models of the Rockwell tester.

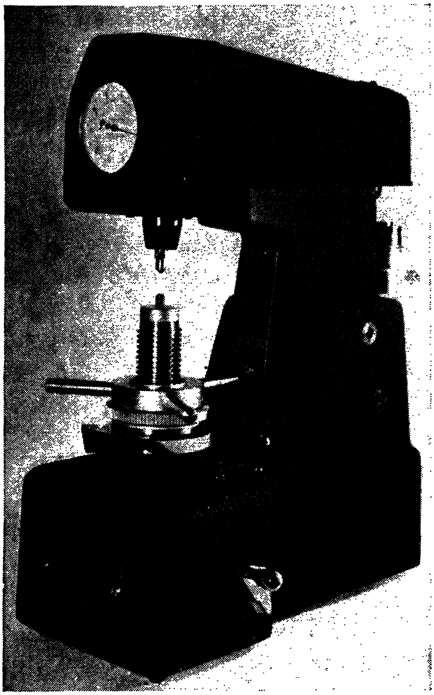


Figure 56. The Rockwell superficial hardness tester.

(Courtesy Wilson Mechanical Instrument Co., Inc., New York, N. Y.)

Penetrators, Loads and Scales

The penetrator used with the Rockwell superficial hardness tester is a sphero-conical diamond tool of the same shape as the Brale penetrator used with the normal model Rockwell tester. Because of the smaller penetration, the penetrators for the superficial models must be shaped with still greater precision than for normal models. They are known as N Brale penetrators to distinguish them from the ordinary Brale penetrator.

The same shape of 120° cone and 0.2 mm radius was used after extensive tests were made with cones from 80° to 120° included angle and radius of 0.05 to 0.33 mm and after sensitivity and practicability had been considered. The diagrams in Fig. 57a and b give some comparisons of depths and diameters of indentations made by different hardness-testing machines on hard steel.

The cycle of operation is the same as in the normal model Rockwell tester. The reading is taken after removal of the major load, but with the minor load still applied.

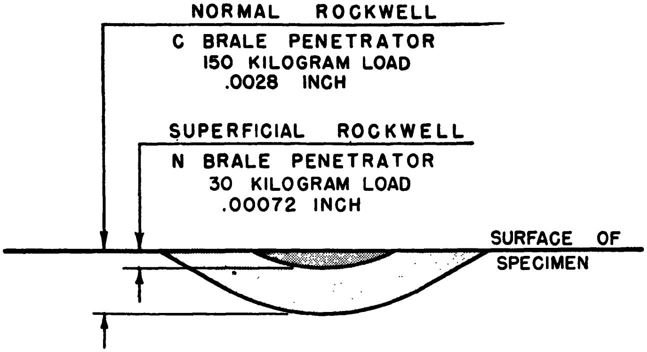


Figure 57a. Comparative depths of penetration in hard steel (C65) as determined on the normal and superficial Rockwell testers.

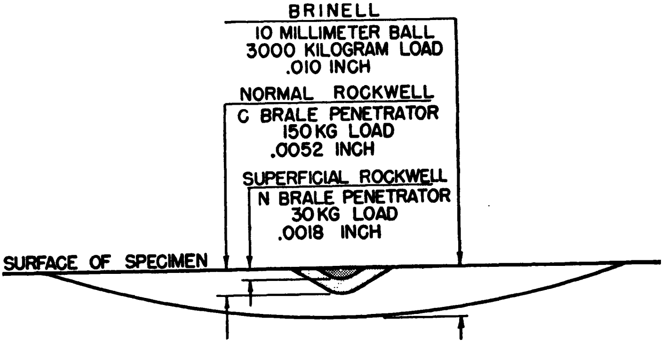


Figure 57b. Comparative depths of penetration in steel (Rockwell C39) on the Brinell, normal Rockwell test and Rockwell superficial tester.

The following system is used for recording readings on the Rockwell superficial hardness tester. The letter N as a prefix to the dial reading has been selected to designate readings obtained using the N Brale penetrator. This letter N is itself prefixed by the major load used and followed by the hardness reading. For example, a piece of hardened steel tested with a major load of 30 kg and diamond penetrator and showing a reading on the dial gauge of 75, would be known as 30N75. Only one set of figures appears on the dial gauge.

For testing soft materials, such as brass, bronze and unhardened steel, the 1/16-in. diameter steel ball penetrator is used. The readings are recorded in the same manner as the N scale, but the letter T designates the use of the 1/16-in. ball penetrator, as for example, 15T, 30T or 45T, depending upon which major load is selected. Penetrator chucks to hold 1/8-, 1/4- and 1/2-in. balls are used for testing very soft materials, for example, plastics, zinc, bearing metals, etc. Table 4 gives the scale designations for the different penetrators.

Table 4. Scales—Superficial Tester

The symbol for use as a prefix to the value read from the dial depends upon the load, type of penetrator and scale from which dial readings are taken, and these symbols are shown below.

Scale Symbol	Penetrator	Load in Kilograms
15N	"BRALE"	15 kg
30N	"BRALE"	30 kg
45N	"BRALE"	45 kg
15T	1/16" ball	15 kg
30T	1/16" ball	30 kg
45T	1/16" ball	45 kg
15W	1/8" ball	15 kg
30W	1/8" ball	30 kg
45W	1/8" ball	45 kg
15X	1/4" ball	15 kg
30X	1/4" ball	30 kg
45X	1/4" ball	45 kg
15Y	1/2" ball	15 kg
30Y	1/2" ball	30 kg
45Y	1/2" ball	45 kg

The major load of 15 kg is applied with a weight pan hung from the end of a power lever. Two small weights added to the scale pan each apply, through the power lever, a load of 15 kg, making the combination of 15, 30 and 45 kg major load.

The sensitivity of the 30N scale as compared to the C scale of the normal Rockwell tester is shown in Fig. 58. Almost the same sensitivity is achieved, although the depth of indentation is less than 1/3.

Thin materials, superficially hardened materials, tests on small areas, or tests where for one reason or another the indentation must be exceptionally small, are made on the Rockwell superficial tester. It offers an advantage in testing soft thin material which has an anvil effect, *i.e.*, if the impression shows through on the reverse side at the point where the test is made, even under light loads of 15 or 30 kg. By supporting this soft, thin piece on an anvil which has a polished diamond at its center, a standardized anvil surface condition is provided. This permits testing such thin pieces on a comparative basis; this would not be possible with a polished steel anvil, as the surface would offer different resistance to the flow of the material as it was used or became indented. This diamond spot anvil should never be used for testing hard material with the N Brale penetrator, for if the hard, thin piece should crack under the testing load, there is the possibility that both diamond penetrator and diamond anvil might break. In writing specifications it should be clearly stated that the material was supported on the diamond spot anvil. The diamond anvil is not used in the normal Rockwell tester, as its heavier loads tend to break the diamond of the anvil.

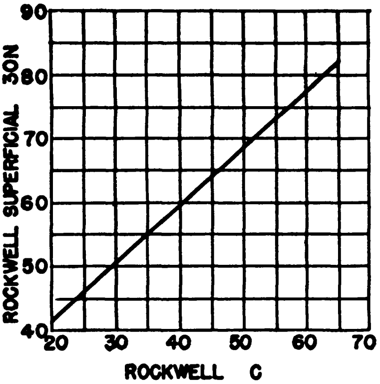


Figure 58. **Showing sensitivity of the 30N *versus* C scales.**

Calculating Depth of Indentations

The depth of indentation for the impression made with the Rockwell superficial tester under increment of minor to major load is obtained by subtracting the reading from 100 and multiplying the result by 0.001 mm or 0.00004 in. By formula:

Depth of major load impression over minor load (mm) = (100 − reading) × 0.001
Depth of major load impression over minor load (in.) = (100 − reading) × 0.00004

The depth of indentation of the minor load is shown in Figs. 59 and 60 for the N Brale penetrator or $\frac{1}{16}$-in. ball T penetrator. This depth, of course, depends on the penetrator and is the same for each penetrator. Convert to 30 kg scale to use curves. The results were obtained from measuring the diameter of minor load indentation and calculating the depth, and are approximate only.

The total depth of indentation may be obtained by adding the minor load impression depth to the depth of impression caused by increment of major load over minor load.

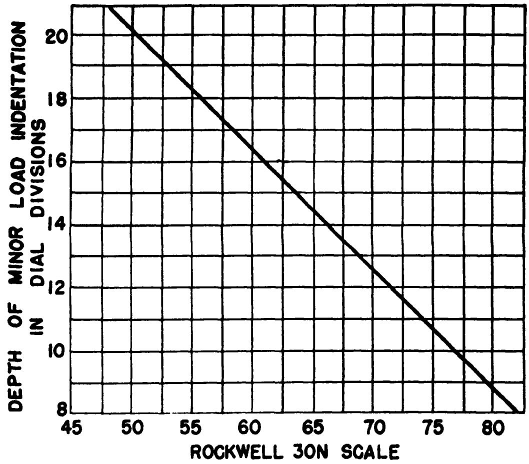


Figure 59. Depth of minor load indentation for Rockwell N scales.

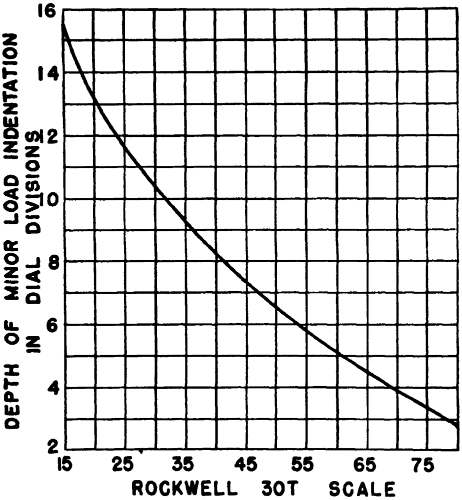


Figure 60. Depth of minor load indentation for Rockwell T scales.

Standardization of the Test

The Rockwell superficial tester is standardized and checked for accuracy in the same manner as the normal model. Test blocks are available for the 15, 30 and 45N and T scales as well as the special scales. A.S.T.M. E 18–42 covers the superficial model as well as the normal model.

Because of the small impressions obtained with the light loads, a smoother surface finish is required than necessary with the heavy load of the normal model. There must be no dirt, scale or any particles on the under surface of the specimen or on the anvil, for in both normal and superficial models any sinking of the specimen under testing load would be added to the actual penetration as measured by the dial gauge. As the size of the impression becomes smaller more care is required in surface preparation.

Material being tested must be supported so it will not move or slip as the testing load is applied; generally a satisfactory support for the normal model will work satisfactorily on the superficial model, although the lighter minor load pressure cannot be used to hold the pieces to the same extent as the 10-kg minor load of the normal model.

As explained in a previous chapter, internal surfaces and large pieces may be tested with special equipment, built with the proper loads for the superficial model. The zerominder scale is available.

Theoretical Considerations

By making proper allowances for the differences in loads in the superficial model and the more sensitive depth-measuring system, all theoretical considerations applying to the normal model will apply to both. Because of the greater and more universal use of the normal model, more study has been carried out on this heavy-load machine. But the general trend in hardness testing is steadily leaning more and more toward testing with light loads, such as are used with the Rockwell superficial hardness tester. Such testing, when applied to finished or semi-finished products in production testing, requires less material to be removed in the final grinding or finishing operation, if it is even necessary to remove the indentation.

Thick material is tested satisfactorily on the superficial model, provided measurement of hardness near the surface is wanted. If the material is homogeneous in hardness that would also be equivalent to a deeper test.

Chapter VII

136° Diamond Pyramid Hardness Method

The 136° diamond pyramid hardness tester, commonly referred to as the Vickers tester, was introduced in England in 1925 by R. Smith and G. Sandland.[1] Its early acceptance by industry was limited to the largest laboratories, and its use was chiefly for research purposes. With the tremendous interest in the nitriding process for surface-hardening of steels which took place about 1930, many metallurgists, in both the United States and Europe, found this test very satisfactory for determining the hardness of thin, superficially hardened material.

Once metallurgists had used the 136° diamond pyramid test in the laboratories and had become familiar with it, its use in testing other than nitrided surfaces become more general in industry because of two outstanding features of the test. The first was the belief that constant hardness numbers were obtained on homogeneous metal, irrespective of the load applied except at very light loads, and the second was the fact that there was a continuous scale from the softest to the hardest metals, including cemented carbides.

The 136° diamond pyramid hardness method follows the Brinell principle in that an indenter of definite shape is pressed into the material to be tested, the load removed, the diagonals of the resulting impression measured, and the hardness number calculated by dividing the load by the surface area of indentation.

The indenter is made of diamond, and is in the form of a square-base pyramid having an angle of 136° between faces. This indenter thus has angle across corners, or so-called edge angle, of 148°6′42.5″. The facets are highly polished, free from surface imperfections, and the point sharp. The loads applied vary from 1 to 120 kg; the standard loads are 5, 10, 20, 30, 50, 100, and 120.

The 136° diamond pyramid hardness number, often designated as DPH, is the quotient of the applied load divided by the pyramidal or surface area of the impression, or by formula:

$$\text{DPH} = \frac{2L \sin \frac{\theta}{2}}{d^2}$$

where L = load in kg

d = diagonal of the impression in mm

θ = angle between opposite faces of the diamond = 136°

Apparatus

The equipment for determining the 136° diamond pyramid hardness number should be designed to apply the load without impact, and friction should be reduced to a minimum. The actual load on the penetrator should be correct to less than 1 per cent and the load should be applied slowly, as it is a static test. The British Standard Institute specification (B.S.I. 427:1931) requires that the full load be maintained for 15 seconds.

To obtain the greatest accuracy in testing, the applied load should be as large as possible, consistent with the dimensions of the test sample. Loads over 50 kg are likely to fracture the diamond, especially when used on hard materials.

The measuring microscope must be capable of measuring to ± 0.001 mm or ± 0.5 per cent, according to B.S.I. 427. The accuracy of the micrometer microscope should be checked against a stage micrometer which consists of ruled lines usually 0.1 mm apart which have been checked against certified length standards. The average length of the two diagonals is used in determining the hardness value.

The corners of the impression provide indicators of the length of the diagonals. The area must be calculated from the average of readings of both diagonals. The impressions are usually measured under vertical illumination with a magnification of about 125×.

The included angle of the diamond indenter should be 136° with a tolerance of less than ± 1°, which is readily obtainable with modern diamond-grinding equipment. This would mean an error of less than ± 1 per cent in the hardness number. The indenters must be carefully controlled during manufacture so the impressions produced will be symmetrical, and there should be no offset at the apex of the diamond. Tables (see Appendix) are available for transforming the values of the diagonals of impression in millimeters to the 136° diamond pyramid hardness number.

There are several instruments for determining this number. One of these is manufactured by Vickers-Armstrong, Limited, of Crayford, Kent, England, and may be best described from the following information from their literature: (see Fig. 61)

> "The machine consists of a main frame *F* of *U* section, which carries the stage *S* and a simple lever *L* of 20 to 1 ratio, applying the load through a thrust rod *Tr* to a tube *T*, which is free to reciprocate vertically, and carries a diamond indenter *D* at its lower end.
>
> "Attached to the main frame is a smaller frame *Fm*, which contains all the control mechanism. The plunger *Pl* reciprocates vertically under the influence of a rotating cam *C*, its purpose being to apply and release the test load. The cam is mounted on

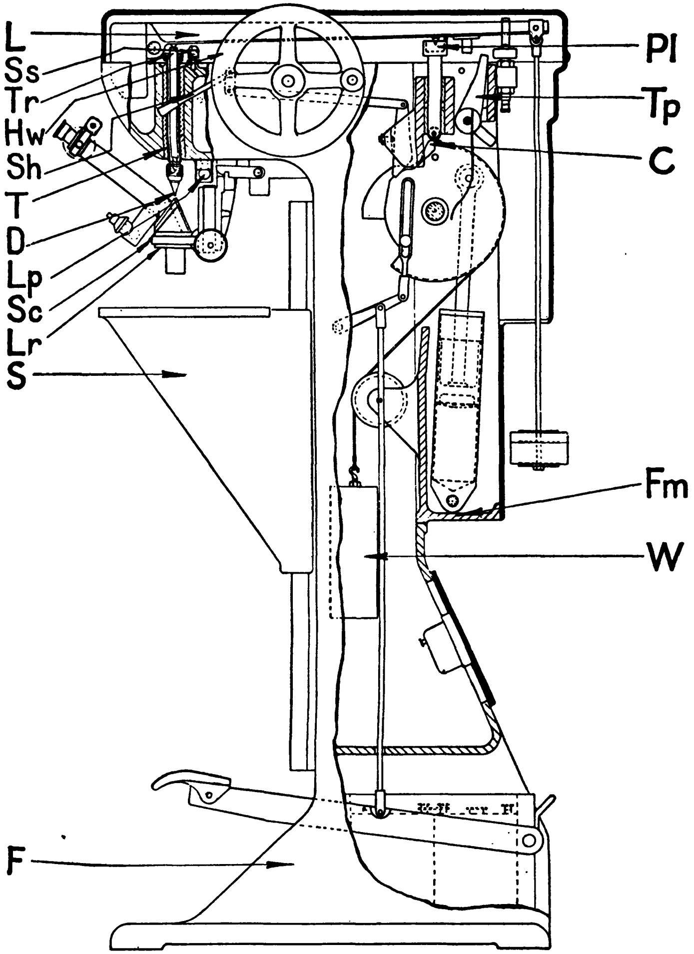


Figure 61. Diagrammatic view of Vickers Tester.

a drum, and when the starting handle *Sh* has been depressed, the whole is rotated by a weight *W* attached by a flexible wire, the speed of rotation being controlled by a piston and dash-pot of oil. The rate of displacement of the oil is regulated by an adjustable control valve. The plunger carries a rubber pad at its upper end, which engages with a cone mounted in the beam, thereby ensuring a very slow and diminishing rate of application for the last portion of the load. Since the cam both lowers and raises the plunger, it will be seen that uniformity of loading and duration of the load is attained, all errors due to inertia and premature removal of the load being eliminated. Depression of the foot pedal returns the cam, drum and weight to their original positions. A tripping piece *Tp* supports the beam during this latter operation, and drops out as soon as the plunger returns to its top position. The machine is then ready for another test."

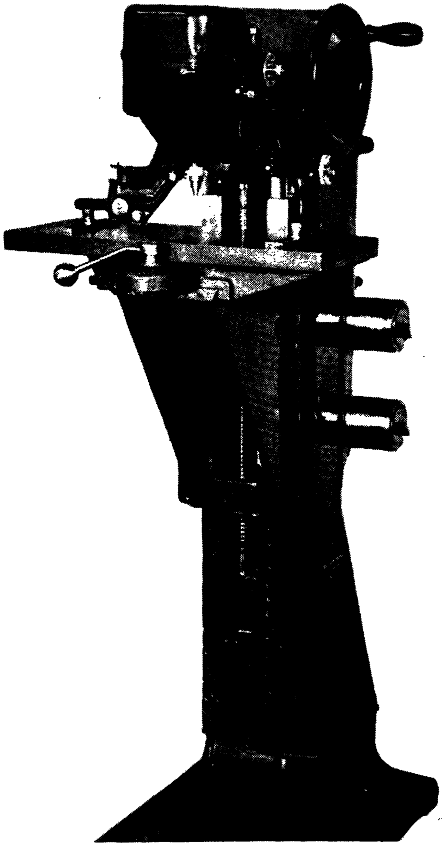


Figure 61a. Vickers tester. (shown diagrammatically in Figure 61.)

(Courtesy of Riehle Testing Machine Division, American Machine and Metals, Inc., East Moline, Ill.)

The microscope is usually mounted on a hinged bracket and may be moved to position over the impression it being necessary to lower the work sufficiently to swing the microscope into position. A specially designed micrometer ocular is provided and the impressions are read to knife edges. The readings are taken from a digit counter mounted on the microscope. Special tables transferring ocular digits to 136° diamond pyramid hardness numbers are supplied. The ocular may be rotated through 90° so that each diagonal may be read. For rapid testing to maximum and minimum limits, a third knife edge is brought into use so that the impressions may be observed to these limits.

Fig. 61a is an illustration of one model of the Vickers tester. In making a test the specimen is placed on a stage which is raised by turning a handwheel on the side of the tester until the specimen nearly touches the diamond indenter. The load is applied by tripping the starting handle, which starts the testing cycle of applying and removing the load. The time taken in the application and duration of the load may be adjusted by an oil control valve in the dash-pot within a range of at least 10 to 30 seconds.

If the work has not been elevated sufficiently for the testing load to be applied satisfactorily, a warning is given the operator by an automatically actuated buzzer. After completion of the testing cycle, the stage is lowered and the microscope brought into position to read the impression. By depressing a foot pedal, the machine is ready for the next test. The stage may be fitted with a V-block for supporting cylindrical work.

If the routine testing is to be carried out, a sliding table may be attached to the stage and the microscope mounted on an auxiliary bracket on the right-hand side of the machine so that testing may be carried on without winding the stage up or down. This is the instrument shown in Fig. 61a.

Another instrument for determination of the 136° diamond pyramid hardness test is manufactured by the Pittsburgh Instrument and Machine Co. of Pittsburgh. The operation is somewhat similar to the instrument described above, except that a red light at the front of the machine shows the time the work is under pressure. A buzzing sound indicates that the work has not been elevated close enough to the diamond. The testing cycle is automatic under motor control and is started by the operator pushing in a button with his foot.

If desired, small-diameter balls may be used as indenters with this equipment; but as it is far more accurate to measure the diagonal of impression than the diameter of a ball impression, most work, regardless of its hardness, is tested with the diamond indenter.

The Rockwell superficial hardness tester is frequently used for determination of the 136° diamond pyramid hardness number. Because of its design, the loads applied are exceptionally frictionless and are very accurate for precision in load application. Separate special sets of weights (Fig. 62) for applying loads of from 5 to 60 kg in steps of 5 kg are available. Likewise, a 136° diamond indenter mounted for use with the Rockwell superficial tester is available.

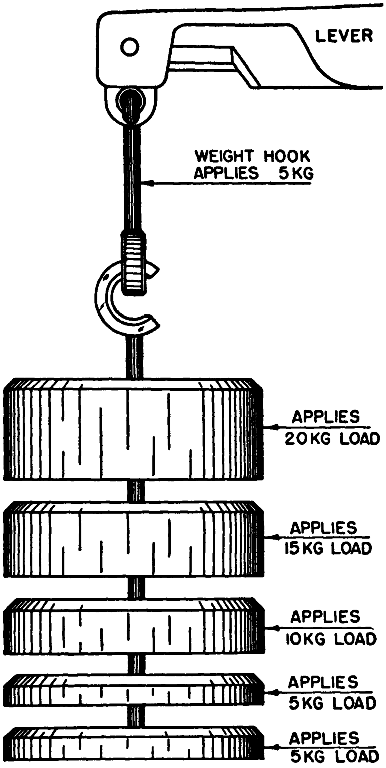


Figure 62. Special set of weights for use with the Rockwell superficial tester for 136° DPH testing.

By using these accessories, properly adjusting the dash-pot, applying the minor load without bringing the dial to set position, and applying and removing the major load, the test is made. No dial readings are taken. The work is then brought under a separate microscope, the impression located, the diagonals read, and the hardness number obtained from tables. By using transferable stages or properly calibrated jigs, the impression may be readily located. A metallurgical microscope with filar eyepiece (Fig. 63) is used for measuring the impression. A magnification of about 125× is used, and the microscope is calibrated with a stage micrometer to transform filar divisions to millimeters. Tables are then used to obtain the hardness number.

A recent development for the determination of the 136° diamond pyramid hardness number is the Tukon Tester manufactured by the Wilson Mechanical Instrument Co. It will be described in detail in a later chapter, but a long range model (Fig. 64) may be used for applying loads up to 50 kg.

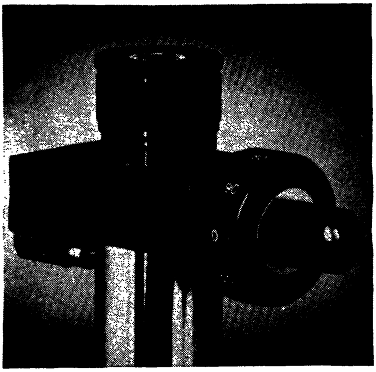


Figure 63. Filar micrometer eyepiece.

(Courtesy Bausch & Lomb, Rochester, N. Y.)

The position where the test is to be made is selected (under a microscope if necessary) and the work on a stage pushed under the 136° diamond pyramid indenter. The indentation is made by elevating the specimen against the indenter until the specimen's hardness resists further indentation. The load then remains applied for a fixed period of time—more than the B.S.I. specification of 15 seconds—and the specimen is automatically lowered so that it may be moved forward under the microscope or ready for the next test. It should be observed that the load is thus applied in a manner different from that of the conventional hardness tester, in that the work is forced against the indenter at a fixed rate. The indenter is always normal to the surface tested and friction is practically eliminated. The entire cycle is automatic. The diagonals of indentation are read by means of the filar micrometer and the microscope is mounted directly on the instrument.

The Firth Hardometer, manufactured by the Firth Brown Tools, Ltd. of Sheffield, England, applies the load through specially calibrated spiral springs compressed by a handwheel. When the load has been applied, a specially designed trip mechanism stops the motion of the handwheel and prevents overloading. The diagonals of the impression may be measured by means of a microscope, or in later models, means are provided to project the impression onto a hooded glass screen where the diagonals are measured. This reduces eyestrain and is of importance where a large amount of routine testing is being done.

Three models are provided: Type F1, which applies a fixed load of either 120 or 30 kg; Type F2, which gives a fixed load of 10 kg; and Type G1, which is a variable-load machine ranging from 2 to 40 kg.

Figure 64. Long range model Tukon tester.

(Courtesy of Wilson Mechanical Instrument Co., Inc., New York, N. Y.)

The Specimen

The surface of the specimen should be flat and polished and supported rigidly normal to the axis of the indenter. According to B.S.I. 427:1931, the center of the impression shall not be less than two and a half times the diagonal of the impression from any edge of the test specimen and from any other impression.

These same specifications state that the thickness of the piece shall be at least equal to one and a half times the diagonal of the impression. As the depth of indentation is about $\frac{1}{7}$ of the diagonal, the thickness should be about 10 times the depth of indentation.

When testing cylindrical surfaces of small diameters the values are only of comparative use, and the diameter of the cylinder should be specified. This is discussed further in the chapter on testing cylindrical surfaces.

Theoretical Considerations

The 136° diamond pyramid hardness number for a given load does provide one continuous scale for testing metal from the lowest value, for example, tin, with a D.P.H. value of 5, to cemented carbides with a value of at least 1500. The impressions are all geometrically similar.

The disadvantage is that although the test is ideal for research and laboratory work, it is not well adapted for routine testing. It is slow, and careful surface preparation of the specimen is necessary, especially when shallow impressions are encountered; the personal element enters into the determination of the diagonal length, and there is the question of eyestrain and fatigue to the operator.

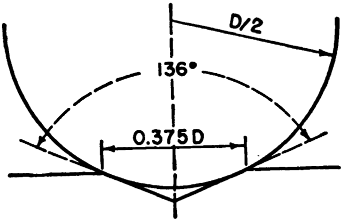


Figure 65. How angle at the apex of the diamond pyramid indenter was determined for use in the 136° diamond pyramid hardness test.

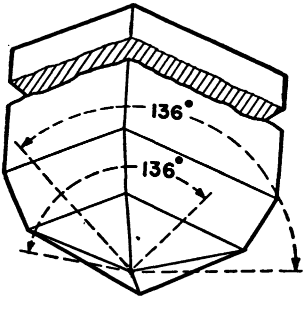


Figure 66. The 136° diamond pyramid indenter.

Because the impressions are geometrically similar, it should follow that the hardness number is independent of the applied load, *i.e.*, on homogeneous material, diamond pyramid numbers obtained with a load of 10 kg should be the same as those made with a load of 50 kg. When Smith and Sandland introduced the pyramid test, the hardness values reported were practically constant under different loads for different materials, whereas these same materials varied considerably when tested with a ball under different loads. The 136° angle was chosen for the pyramid as it represented the most desirable ratio of indention diameter to ball diameter in the Brinell test. This is shown in Fig. 65; the ratio is 0.375. Fig. 66 shows the form of the indenter.

Furthermore, experience has shown that in general the diamond pyramid hardness number is independent of load when determined on homogeneous metal, except possibly at light loads. However, it is desirable to report the load employed in every case and B.S.I. 427 recommends the designation $H_D/20 = 500$. This would mean a diamond pyramid hardness number of 500 determined under a load of 20 kg. Knowing the load employed enables one to judge the accuracy and sensitivity of the test; furthermore, it assures duplication of results if the test was not made on homogeneous materials, as for example on case-hardened steel. If, as has been found by some observers, there is a drop in the hardness value as the testing load is increased when testing such materials as mild steel and soft copper, the designation of the load employed will be advantageous.

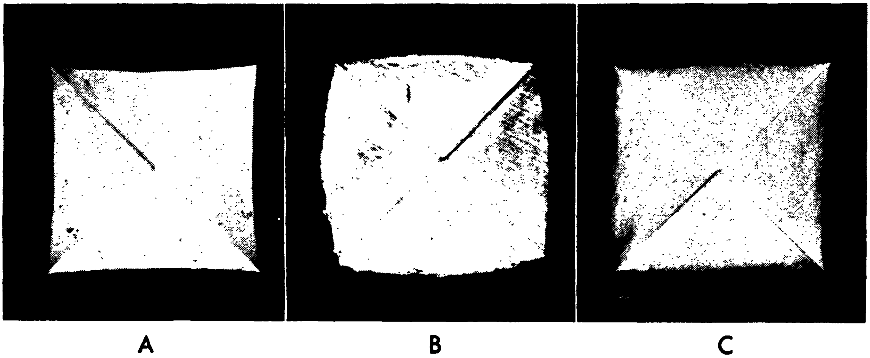
It is also necessary to consider the effect of "ridging" and "sinking" of the metal at the surface of the material being tested. H. O'Neill[2] gives a very adequate description of these phenomena:

> "In the pyramid test, piling-up does not produce a concentric ridge, for while metal is then extruded upward along the faces of the indenter, it remains practically at the original level near the corners. The resulting bulge-effect of the sides of the square impression as seen under the microscope has been termed 'convexity' and appears also in the Haigh prism test. In such a case, the diagonal measurement gives a low value of both the projected and the contact areas of the indentation, and produces erroneously high hardness numbers. Sinking-in gives likewise a partial downward curvation of the metal which is known as 'concavity.' The diagonal measurement here caused high values of area and erroneously low hardness numbers."

Errors as high as 10 per cent in hardness numbers using the conventional formula may appear on different metals due to these effects. More recent work along this line will be discussed in the chapter on testing thin sheet material. Fig. 67 illustrates "sinking," "ridging" and normal type of diamond pyramid indentations.

When the material surrounding the impression is piled up or ridged, the metal is generally cold-worked and convex impression results. With annealed materials concave sides are produced. Plastic flow around a pyramid is not uniform in any horizontal section. Elastic recovery for specimens in the upper range of hardness is appreciable in the pyramid test and affects to some extent the length of the measured diagonal.

The question of relative sensitivity of the diamond pyramid test as compared to other tests, such as the Rockwell C scale, should be considered. It is not possible to read actual diamond pyramid hardness numbers. They are obtained from a formula derived from readable units on the microscope ocular or filar. The readable unit is usually 0.001 mm and the hardness number tables are figured in units of 0.001 mm. The Rockwell C scale is usually read to the nearest half point. Fig. 68 is a plot of Rockwell C scale readings vs. diamond pyramid hardness numbers and ocular readings. Each ½ point Rockwell number is the same value as each readable ocular, *i.e.*, each unit is 0.001 mm. It will be seen that for a load of 10 kg, the diamond pyramid hardness is comparable in sensitivity if readable units are considered. If the diamond pyramid hardness number is considered, then an imaginary relationship exists, because one cannot read D.P.H. 800, 799, 798, etc. This same reasoning holds in comparing Brinell numbers or any number expressed by a relation L/A to hardness numbers expressed by a linear scale. On the other hand if the load used in the diamond pyramid hardness test is 50 kg, it becomes more sensitive than the Rockwell C scale.


A B C

(*Courtesy R. H. Heyer*)

Figure 67. Diamond pyramid indentations.
A. "sinking" type; B. "ridging" type; C. normal type.

With properly prepared samples, *i.e.*, those which give well defined impressions, provided with proper supports, so that regularly shaped impressions are produced, and with the necessary care being taken to determine the correct measurements of the impression, the 136° diamond pyramid hardness number may be obtained to close limits, if the apparatus meets the requirements set forth above. Impression diagonals may be determined to ± 0.001 mm. This difference varies in significance in different parts of the hardness scale and with the load employed, but the overall accuracy is good and satisfactory for most purposes.

With a load of 30 kg, a difference of 0.001 mm equals 8 D.P.H. numbers in the hardness range of 950; as the load is reduced to let us say, 10 kg, this difference amounts to 14 D.P.H. numbers. These examples show why it is necessary to have proper equipment, carefully prepared samples, and exact determination of the impression length, to obtain comparable results.

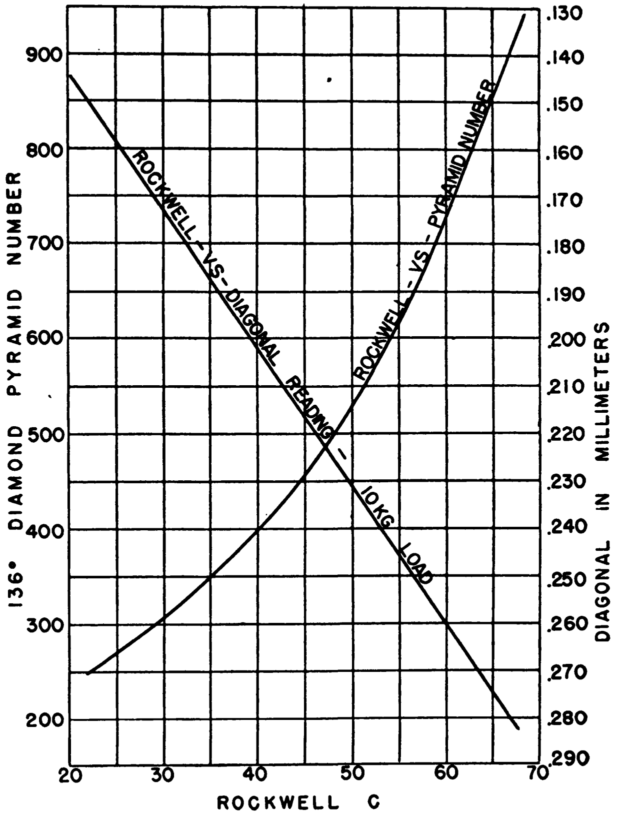


Figure 68. Comparative sensitivity of Rockwell C scale *versus* diagonal readings and diamond pyramid hardness numbers (10 *kg* load).

References

1. Smith, R. L., and Sandland, G. E., "Some Notes on the Use of a Diamond Pyramid for Hardness Testing," *J. Iron Steel Inst. (London)*, III (1925).
2. O'Neill, H., "The Hardness of Metals and Its Measurement," Cleveland, Sherwood Press, Inc., 1934.

Chapter VIII

Other Hardness Testers

In addition to the four most commonly used indentation hardness methods, which have been described in the previous chapters, there are other methods which should be explained. These generally meet the requirements of some particular field of testing and are related, in some cases, to the methods already described. They are the Monotron, the Gogan, Herbert Pendulum and the Baby Brinell. Some of these might have been appropriately described in earlier chapters as, for example, the Gogan and Baby Brinell machines could have been discussed under Brinell testing. However, the Gogan machine definitely applies a minor load, and this would make it somewhat similar to the Rockwell test, even though the loads differ greatly.

THE MONOTRON

The Monotron, manufactured by the Shore Instrument and Mfg. Co., Jamaica, L. I., is a direct-reading static mechanical pressure hardness tester, which registers on a dial the Monotron number, which is the load required to produce a definite penetration in the material under test. Two indicating dial gauges are used in conjunction with it—one for measuring the applied pressure and the other for measuring the depth of penetration.

In making the standard test, a ¾-mm spherical diamond penetrator is forced into the specimen to a depth of 0.045 mm (9/5000 in.) and the Monotron hardness number is obtained while the load is applied. The number is the load in kilograms, and the scale is designated as C–D scale. An equivalent scale is calibrated in Monotron diamond Brinell numbers, which is kilograms per square millimeter. This is the M-1 scale.

Other penetrators used for testing dead-soft materials are 1-mm, 1/16-in. and 2½-mm diameter balls. These are made from cemented carbide. The results of tests with these penetrators are designated as the M-2, M-3 and M-4 scales, respectively. Whereas the C–D or M-1 scales cover the entire range of metals from soft to hard, the M-2, M-3 and M-4 scales are used to increase the sensitivity of the test on dead-soft metals.

As the pressure is applied by the operator in making the test its increasing value is indicated on a pressure gauge, and the resulting increase of penetration is shown on the depth gauge. It is necessary for the operator to read both dials, one after the other. The accuracy of the applied load depends on that of the pressure gauge; the accuracy of the depth gauge is of extreme importance, as the Monotron readings are based on a depth penetration of only 9 divisions on the dial. In making the test, the specimen is placed firmly on the test table. As the hardness depends on the depth measurement, a firm, unyielding seat is required, as in the Rockwell test. A lever is used to bring the testing head down until the work is contacted and the depth indicator hand begins to move. The depth gauge is then set to zero and the load increased until the depth gauge has traveled the nine divisions, or 9/5000 in. Then the hardness number is observed. For production testing, a double hand with an angle equivalent to nine divisions is used.

When the load is released, the depth indicator needle returns toward zero to the extent of the elastic recovery of the test piece. The remaining divisions above zero indicate the degree of permanent deformation. Shortening or compression of the penetrator and its holder unit is neutralized by a compensator.

The surface may be prepared or unprepared. When testing unprepared surfaces, a prepressure is used to force the penetrator through the scale, or rough surface, and the starting point of the pressure hand is then set 10 or 20 more kilograms below zero. When the pressure hand has been brought to zero, the depth indicator hand must penetrate further for the standard testing depth of 9/5000 in.

Thin metal down to 0.020 in. may be tested without anvil effect. Thin, superficially hardened material, such as nitrided steel, may be tested by taking the sum of three readings of three divisions each, rather than a single reading of 9 divisions.

The Monotron has a great deal of flexibility and is extremely rapid. The personal element involved in making the test, eye fatigue, and the difficulty of obtaining close agreement between different machines are the main factors in the limited application of the Monotron in industry.

GOGAN TESTER

The Gogan Hardness Tester, manufactured by the Gogan Machine Corps. of Cleveland, Ohio, is based primarily on the Brinell method, but in addition a minor load is employed. The machine is direct-reading and the Gogan hardness number is the depth in millimeters to which a 10-mm diameter steel ball penetrator is forced into the metal under a load of 3000 kg beyond the depth it was previously driven by a minor load of about 1350 kg. The reading is taken with the load applied. The minor load is adjustable and test blocks furnished with the instrument may be used to adjust the minor load to give the correct Gogan number.

A conversion chart gives equivalent Brinell numbers and Brinell diameters for the various Gogan numbers on different materials to be tested. Compensation is allowed for the deformation of the ball and machine under load.

As the major load is 3000 kg, which may be checked by a Brinell Proving Ring, the impression diameter may be read with a Brinell Microscope to determine the Brinell number directly, provided the surface of the material is suited for a Brinell test.

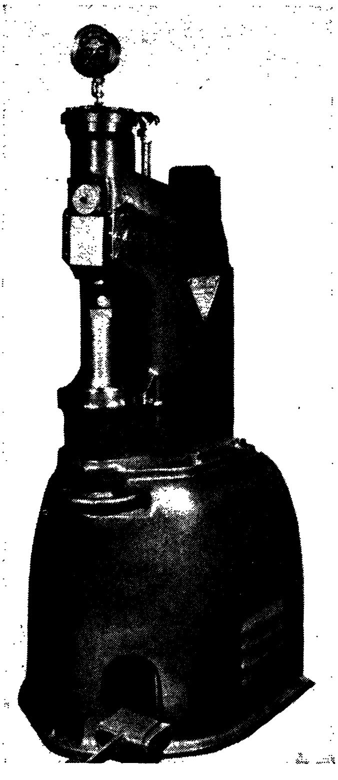


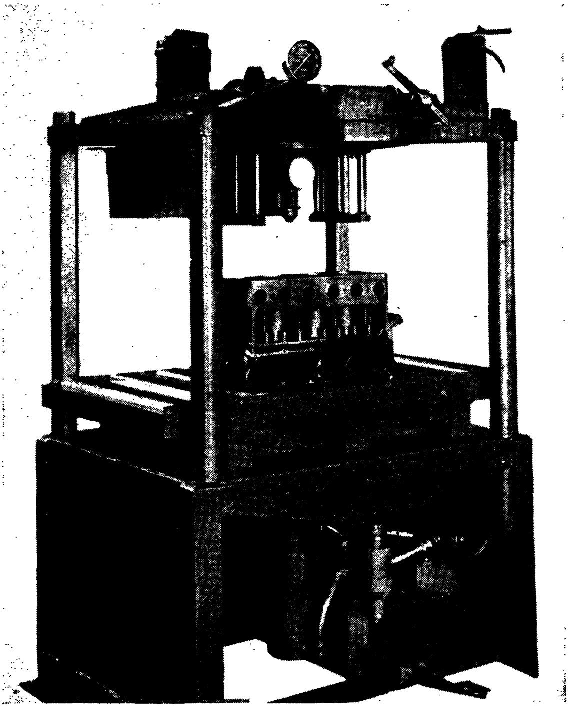
Figure 69. Gogan tester.

(Courtesy Gogan Machine Corp., Cleveland, Ohio)

The machine is semi-automatic in operation, the testing cycle being started by a foot pedal. It is extremely rapid; as many as 30 tests per minute have been made in testing pieces that can be readily handled.

The loads (both minor and major) are applied by hydraulic pressure with an accuracy of 0.33 per cent. After the minor load is applied, a magnetic clutch is energized and the depth of penetrator (the Gogan number), caused by the application of the major load, is indicated on the dial gauge. In making the test, the operator inserts the piece on the anvil and presses a foot pedal, which starts the cycle for applying minor and major loads. The depth-measuring dial gauge is activated through the magnetic clutch to measure the depth of penetrator after the minor load is applied. Fig. 69 illustrates the floor-type model 911.

The machine is used for production testing of steel, brass, cast-iron and malleable iron parts. Because of the heavy minor load, which penetrates to a depth of about 0.020 in. in soft steel, the machine is used to test parts with decarburized surfaces, such as automobile leaf springs. It may also be used to test rough castings and forgings.



(Courtesy Gogan Machine Corp., Cleveland, Ohio)

Figure 70. Semi-special Gogan tester.

In practice the Gogan limits are determined by experiment so that a correlation is found between actual Gogan numbers determined on rough surfaces and decarburized surfaces, as compared to true Brinell numbers. As the test is on a comparative basis, this instrument serves well for rapid production testing of such parts as mentioned above. Any effect due to impact or not applying the load for 30 seconds, as in the standard Brinell test, is compensated for in the experimental relations.

As the machine is used for production testing, it is often located on the assembly line. Fig. 70 shows a semi-special model used for testing large and irregularly shaped pieces.

THE HERBERT PENDULUM HARDNESS TESTER

The Herbert Pendulum Hardness Tester was formerly manufactured by Edward G. Herbert Ltd. of Manchester, England, but its manufacture was discontinued during World War II and at this writing has not been resumed. It will be described here briefly, mainly because it provides an extremely sensitive method of differentiating minute differences in hardness. It is a very fascinating and ingenious instrument and it is used by physicists more than by metallurgists. It finds little, if any, use in the inspection department.

The Herbert Pendulum consists of an arched metal casting weighing 4 kg, which oscillates as a pendulum about 1-mm diameter ball pivot. The pivot may be either steel, ruby or diamond. Directly above the ball is a graduated weight on a screw, which may be raised or lowered to bring the center of gravity of the instrument to a predetermined distance above or below the center of the ball. For standard tests, this distance is 0.1 mm below the center, and the time of a single swing on a very hard surface is 10 seconds.

Two independent tests are made: (a) time tests and (b) scale tests. The time hardness number is the time in seconds for ten single swings. Typical approximate results are:

Glass	100
Fully hardened carbon steel	85
Annealed carbon steel	22
Rolled brass	15
Lead	3

The scale hardness number is the number on a scale located on the top of the pendulum to which a bubble traverses from 0 at the end of one swing of the pendulum. The initial position of the pendulum is a tilted one in which the center of the bubble is at 0. The scale has 100 divisions; on a very hard surface the bubble travels almost the entire 100 divisions in the first oscillation, when the pendulum is placed carefully on the hard surface and tilted to 0 and released. When testing lead, the pendulum will not swing at all but remains at 0. Typical scale hardness values are:

Glass	97
Fully hardened carbon steel	93
Annealed carbon steel	40
Rolled brass	14
Lead	0

It is claimed that the time test measures resistance to indentation, whereas the scale test measures the resistance of the material to working.

The test requires careful manipulation and also great care in the preparation of the specimens surface.

BABY BRINELL

Prior to the invention of the Rockwell hardness tester, there was no satisfactory method of determining the hardness of sheet metal. There was need for a test to estimate the suitability of sheets for drawing and press working, and a need to know the effects of various degrees of cold work and subsequent annealing.

The standard Brinell test of 3000 kg and 10 mm diameter ball required a test specimen about 0.4 in. thick. Reducing the load to 500 kg, the thickness may be reduced to something in the order of 0.25 in. for soft material (Brinell 50) and 0.050 in. for hard metal (Brinell 200). This left open the accurate testing of thinner sheets.

Work was carried on in England during World War I, using lighter loads and smaller diameter steel balls, but the details of the work are sketchy. However, in this country the problem was studied by the Control Laboratory, Inspection Division, Ordnance Department, U. S. Army. As a result of their studies in connection with the hardness testing of cartridge brass down to 0.010 in., the Baby Brinell test was developed.

A $\frac{1}{16}$-in. diameter steel ball was used and the load was 15 kg. The diameter of impression was measured with a 16-mm objective lens and a filar micrometer type eyepiece.

Loads of from 5 to 25 kg were studied and the final selection of 15 kg was to some extent arbitrary. Lighter loads failed to give sufficient sensitivity to the test and heavier loads caused cupping of the thin sheets. A $\frac{1}{16}$-in. diameter ball rather than a 1-mm ball was selected because of its availability in this country.

The original apparatus was quite simple, consisting chiefly of a sensitive Troemner laboratory scale. Considerable difficulty was experienced in the method of applying the load with this type of equipment, with the result that several experimental models were built. The final design applied the load by dead weight under dash-pot control.

The test has some application for sheet metal at the present time, but the development of the 136° diamond pyramid test, as well as the use of the Rockwell and Rockwell superficial hardness testers, have made it almost obsolete. It still appears in a few important specifications and this justifies its description here.

The test has now been changed to apply a load of 12.6 kg and a $\frac{1}{16}$-in. ball penetrator is used. This load and penetrator correspond to a 500 kg

In the case of depth-measuring instruments, the conditions are further complicated by the requirement of the test that the piece shall not move or slip in the slightest degree as the testing loads are applied. No movement of any of the parts comprising the depth measuring system is permissible.

All portable instruments must provide means for accurately lining up rounds so that the top of the radius of curvature is directly underneath the center of the penetrator.

THE FILE TEST

The simplest form of portable hardness tester is the file; and while it is not an instrument, it so completely meets the requirements of a test by a portable instrument insofar as hardened steel is concerned that it will be discussed at this time.

The file test for hardness consists essentially of cutting or abrading the surface of the metal parts with files, and approximating the hardness of the surface by the "feel" or extent the files bite into the surface.

Special hardness-testing files are hardened to Rockwell C66–67. Undoubtedly, the basis of the file test is the fact that files at Rockwell C66–67 will not appreciably cut hardnesses at C65 or higher, and further that the fileability of steel parts less than C65 increases gradually as the Rockwell hardness decreases.

Good high-grade testing files as, for example, Nicholson hardness testing files, are made to cut high-carbon steel hardened and tempered to Rockwell C63–64. Metal parts which are practically unfileable are said to be "file hard." The exact point at which fileability ends and "file hardness" begins is a controversial matter. However, a reasonable approximation of the end of fileability for most steels is Rockwell C64.

It is known, on the other hand, that very highly alloyed steels, such as high-speed steels in the untempered condition, are sometimes not fileable at hardness as low as C62. Practically, therefore, it may be necessary for the inspector to set up his own interpretation of the limit of fileability for certain steels.

The file test is most generally used to determine the hardness of tools or other hardened parts which, after hardening or hardening and slight tempering, are expected to be file hard, or nearly so. Under such conditions the file test is best conducted by firmly applying the file to the surface to be tested, and with short, firm strokes attempting to "feel" how the file bites the surface. If the file cannot bite, the surface is judged to be "file hard." If the file bites slightly, the surface may be judged to be C63, 62 or 61, as the case may be. It should be borne in mind that the accuracy in the ability of an operator to judge hardness falls off rapidly as the difference between "file hard" and the actual hardness of the piece increases.

The file test is often used to test parts which are heat-treated to Rockwell specifications and it is desired to inspect the hardness in certain areas which are not accessible to testing with a Rockwell tester. In such cases, the samples often are considerably less than file hard, and it is necessary to resort to the use of test blocks to render the file test more accurate. By comparing the "feel" of the test file on the surface of the part to be tested with the "feel" of the file on test blocks of known hardnesses, which vary in hardness by small increments, it is possible to determine the hardness of the specimen, as this is equivalent to the hardness of the test block with which it most nearly compares.

The file test is sometimes used for determination of soft spots or decarburization.

In using the file it is important to realize that the file can be an extremely useful tool if good judgment is exercised in its use. File testing is an art acquired by experience and in the hands of a skilled workman it can be very helpful.

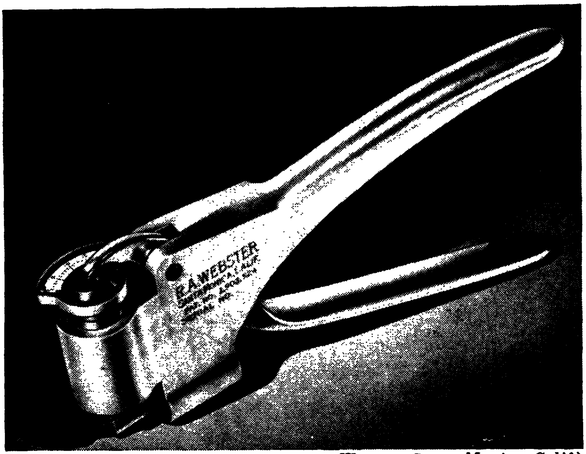
WEBSTER HARDNESS GAUGES

Webster hardness gauges, manufactured by R. A. Webster of Santa Monica, California, are made in three distinct models. All three operate in the same manner but differ in penetrators, scales, and range of hardness covered. The gauges are all light and portable and are often referred to as "Webster pliers." The three models are: Model A, B and B-75. Model B is illustrated in Fig. 71. The work to be tested is placed between the anvil and penetrator. Pressure is applied to the handles until "bottom" is felt, at which time the dial indicator is read. Additional pressure does not give an inaccurate determination.

In operation, as handle pressure is applied the penetrator moves toward the work until contact is made. Further pressure causes the penetrator to indent, and the load is provided by compressing a spring in the penetrator housing. The dial gauge is attached to the upper end of the penetrator housing and is actuated by the movement of the penetrator. The Model A gauge has a four-point penetrator and a dial indicator graduated 1, 2, 3, and 4, which shows the number of impressions being made by the penetrator on the metal being tested. The amount of pressure exerted on the penetrator is determined by the adjustment of the load spring. With a given setting of the load spring, the number of impressions will depend on the hardness of the metal being tested.

The Model B gauge has a single-point penetrator and the dial indicator is graduated from 1 to 20; the hardness readings obtained may be compared to other hardness scales, such as Rockwell values, by conversion. This model is so designed as to be used for checking aluminum alloys.

The Model B-75 gauge is more sensitive than the Model B gauge and is designed for use on brass. By use of specially designed levers, the sensitivity of the B and B-75 gauges may be increased.



(*Courtesy R. A. Webster, Santa Monica, Calif.*)

Figure 71. Model B Webster gauge.

The gauges are primarily used to determine whether an alloy is hard or soft. Their principal field is in the aircraft industry in connection with the testing of thin sheet aluminum and its many alloys. The gauges are rugged and can stand hard use.

THE BARCOL IMPRESSOR

The Barçol Impressor manufactured by the Barber-Colman Company of Rockford, Illinois, is shown in Fig. 72. It measures hardness by the depth of indentation made by a hardened steel truncated cone penetrator with an included angle of 26 degrees with a flat tip of 0.0062 inch in diameter. The penetrator fits into a hollow spindle and is held down by a spring-loaded plunger. The depth of penetration under the spring-loaded pressure is transmitted to a dial indicated by a lever. The hardness scale on the dial has 100 divisions, each representing a depth of about 6.4 microns. The maximum indentation is $\frac{1}{32}$ in., which is obtained only when testing the softest materials. In making the test, the leg plate in the rear of the instrument is set on the surface to be tested and a pressure of about 16 pounds applied against the point by pressing on the instrument housing; the hardness number is then read. The field served by this instrument is usually in testing completed assemblies or small parts in subassemblies, when it would be costly to disassemble and test in the conventional manner.

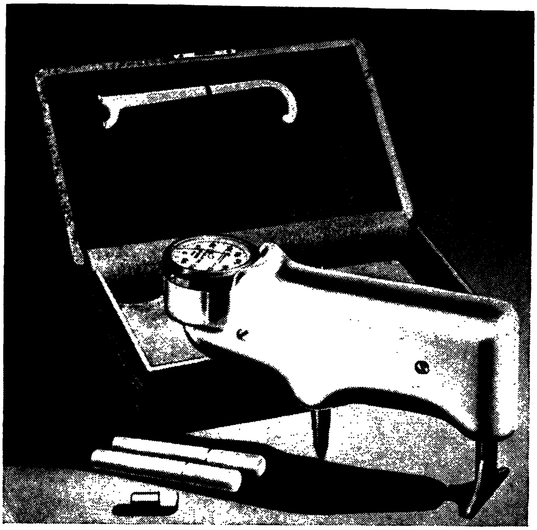


Figure 72. Barcol impressor.

(Courtesy Barber-Colman Co., Rockford, Ill.)

KING PORTABLE BRINELL

Probably the most accurate and most widely used of all portable hardness testers is the King Portable Brinell tester. It is shown in Fig. 73 and is manufactured by Andrews King of Narberth, Pa. The instrument is made in two models. The one most commonly used applies a load of 3000 kg to a 10-mm diameter ball and the pressure is applied hydraulically; an accurately designed poppet-valve prevents overloading no matter how much the machine is pumped. A second model applies loads varying from 125 to 1000 kg and is known as the nonferrous model. Both models have a depth of throat of 4 in., a height of gap of 10 in., and weigh about 26 pounds. The test head is removable for testing large parts. It is used in rolling mills, steel mills, foundries, machine shops, etc. It is particularly well adapted to testing car wheels, axles, large castings, rails, etc.

BRINELL HAMMER

Another form of portable Brinell hardness tester, operating on an entirely different principle, is called the Brinell Hammer, and is manufactured by the Steel City Testing Laboratory of Detroit, Michigan. It is recommended for testing specimens which cannot be conveniently tested in the conventional machines. It is not intended to give the true Brinell number and is merely a comparator; it is rapid and is satisfactory where only approximate results are needed.

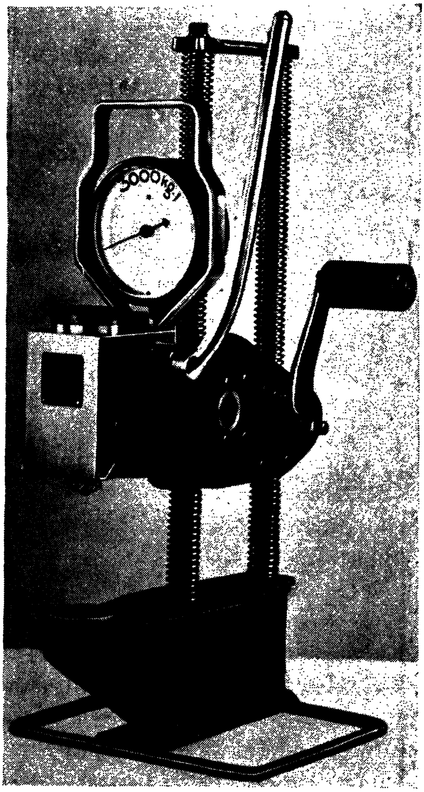


Figure 73. King portable Brinell.

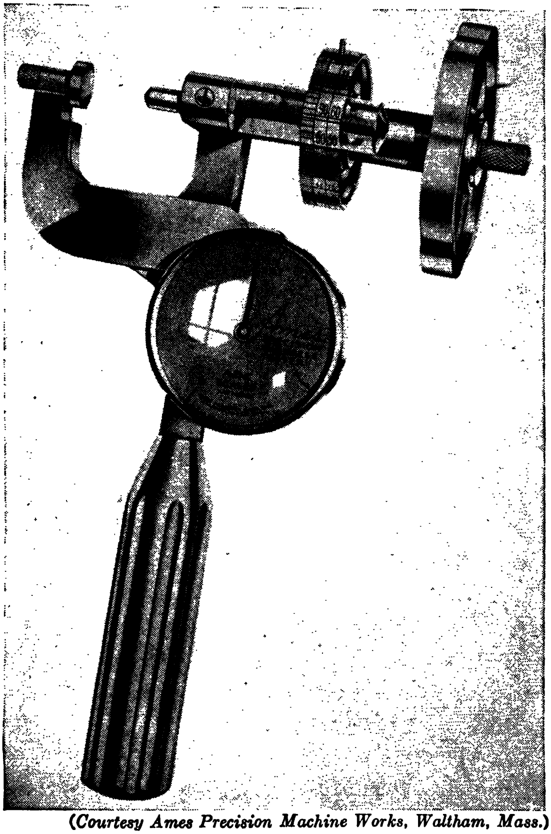
(Courtesy Andrews King, Narberth, Penna.)

The hardness of the piece being tested is compared to the hardness of a known standard, and if the impression is smaller or larger, the specimen is either too hard or too soft. The impression is checked by a microscope and results compared with values shown on a chart supplied with the hammer.

In making a test the hammer is rested on the specimen to be tested. A piston under spring pressure is released against a striking bolt causing the testing ball to strike against the specimen. The instrument is reset by a spring action.

THE TELEBRINELLER

The Telebrineller instrument is manufactured by Teleweld, Inc., of Chicago. It is a comparator. A soft rubber head rests on a test bar of known Brinell hardness. Below the bar, in a narrow aperture in the base of the head, the impression ball is secured and is in contact with the bar of known hardness and the bar to be tested. When the anvil is struck with a hammer, the impact is applied equally to the bar of known hardness and the piece to be tested. The diameters of the impressions are directly related to the hardness of both metals. After the test, the bar of known hardness is moved to a clear area for the next test.



(Courtesy Ames Precision Machine Works, Waltham, Mass.)

Figure 74. Ames portable hardness tester.

The diameters of impressions are measured with a microscope similar to the Brinell microscope. A simple ratio of the diameters measured, multiplied by the hardness of the known Brinell test bar, gives the hardness of the piece being tested; or by formula:

$$\frac{\text{Dia. of impression of test bar}}{\text{Dia. of impression of specimen}} \times \text{Brinell hardness of test bar} = \text{Hardness of specimen}$$

The instrument is used in foundries for testing large castings; in railroad work for testing hardness of rails; for testing welds; for pipe lines and oil refineries, etc.

OTHER PORTABLE TESTERS

There are many other portable hardness testers. The Ames Precision Machine Works of Waltham, Massachusetts, manufactures a portable tester using the same loads as does the Rockwell tester. The loads are applied by a screw action with a handwheel to the frame of a micrometer and measured on a calibrated dial gauge. The depth of indentation is measured by the micrometer screw. The instrument is portable and weighs only a few pounds (Fig. 74). Either a diamond cone penetrator or a ball penetrator may be used. Results are probably accurate to within ± 2 or 3 Rockwell numbers.

Another portable indicator consists of a set of steel pins of Rockwell hardness C46 to 62 in steps of 2 Rockwell numbers. The piece to be tested is scratched with each pin until one scratches and the next one lower slides over the piece to be tested. The hardness of the specimen lies between the 2 Rockwell number interval between the pins. This product is made by the M. C. Layton Ltd. of London, England.

Files tempered to different Rockwell hardness values and ground to a needle point at the file end represent another scheme similar to the one described above. The test is made by determining the softest file which will scratch the surface of the specimen.

A large number of portable testers were formerly manufactured in Europe. These include the well-known Poldi tester, which operates simply by striking a holder to release a ball which impresses both a sample of known hardness and the sample to be tested. By measuring the diagonals of the impressions it is possible to calculate the hardness of the unknown specimen.

Several portable testers were formerly manufactured by Louis Schopper of Leipzig, Germany. Most of these operate on a principle similar to one of the portable instruments described in this chapter.

Chapter X

Hardness Conversion Relationships

Although the different hardness testers described in the previous chapters are generally used for testing of metals in the fields in which each excels, situations often arise in which one hardness—as for example, the Brinell—is needed when only the Rockwell number can be obtained, or *vice versa*. Or it may be that a Brinell number is incorrectly specified for a metal so thin that it may be tested accurately only with a light load-applying tester such as the Rockwell tester. Under such conditions so-called "conversion" charts of different hardness scales are used. Such charts generally include also tables showing the relationships between various hardness scales and tensile strength.

A multitude of such conversation tables are in use and wide discrepancies occur in the values published in different charts. It is only natural that such discrepancies exist because different tables have been prepared using machines which were inaccurate and not properly calibrated before making the tests. The test specimens may not have been properly selected and prepared, or the tests were made on a single type or restricted range of materials, whereas the user of the chart may apply it to materials which require quite different conversion relations.

Furthermore no conversion is mathematically exact or can be made mathematically correct for a wide range of materials. Different loads, different shapes of penetrators, homogeneity of specimen and cold-working properties of the metal all complicate the problem.

It must also be pointed out that the use of different compositions in Brinell balls, such as hardened steel balls, Hultgren balls, and carbide balls, may give different Brinell numbers; hence the type of ball used should be specified.

The reliability of all conversion tables depends on the care with which they have been prepared. Limitations of testing equipment and poor sensitivity of the scale used are possible sources of errors.

Any hardness test should be made with the largest load available consistent with the dimensions and characteristics of the specimen as well as the largest allowable impression size. Conversion between tests made with comparatively light loads having poor sensitivity and heavy loads with good sensitivity may give poor results.

It has been pointed out that Scleroscope readings are subject to many errors not found in static indentation tests; therefore, conversion tables involving Scleroscope readings will be influenced by these factors.

Early Work

The early charts were prepared by making tests on a large number of metals, thus obtaining sufficient data for determining the relation. Such work was carried out by R. R. Moore,[1] S. C. Spalding,[2] J. H. Cowdrey,[3] R. C. Brumfield,[4] and others. There were considerable differences in these relationships and in 1930 the National Bureau of Standards published Research Paper No. 185 entitled, "Relationships Between Rockwell and Brinell Numbers," prepared by S. N. Petrenko. This was very complete and the following is a summary of it.

1. "The experimental indentation numbers made it possible to obtain semiempirical formulas for calculating Brinell numbers from Rockwell numbers, or *vice versa.* When used over the range specified each of these formulas gives values in which the error to be expected is not greater than plus or minus 10 per cent."

These equations are:

$$\text{Brinell} = \frac{7{,}300}{130 - \text{Rockwell B}} \text{ for Rockwell B greater than 40 and less than 100.}$$

$$\text{Brinell} = \frac{3{,}710}{130 - \text{Rockwell E}} \text{ for Rockwell E greater than 30 and less than 100.}$$

$$\text{Brinell} = \frac{1{,}520{,}000 - 4{,}500 \text{ Rockwell C}}{(100 - \text{Rockwell C})^2} \text{ for Rockwell C greater than 10 and less than 40.}$$

$$\text{Brinell} = \frac{25{,}000 - 10\,(57 - \text{Rockwell C})^2}{100 - \text{Rockwell C}} \text{ for Rockwell C greater than 40 and less than 70.}$$

2. "For steels the tensile strength may be calculated from the Rockwell number, with expectation of an error less than 15 per cent, by using the empirical formulas":

$$\text{Tensile strength (lbs/in.}^2) = \frac{4{,}750{,}000 - 12{,}000 \text{ Rockwell B}}{130 - \text{Rockwell B}} \text{ for Rockwell B greater than 82 and less than 100.}$$

$$\text{Tensile strength (lbs/in.}^2) = 10^5 \frac{(7{,}000 - 10 \times \text{Rockwell C})}{(100 - \text{Rockwell C})^2} \text{ for Rockwell C greater than 10 and less than 40.}$$

3. "No discernible relationship was found between the tensile strength of non-ferrous metals and their indentation numbers." This work of the Bureau points out that earlier investigators had established the fact that a rough proportionality existed between the tensile strength of steels and its Brinell number. Such relationships expressed in equations were:

Tensile strength (lbs/in.^{2}) = 515 × Brinell for Brinell numbers less than 175.
Tensile strength (lbs/in.^{2}) = 490 × Brinell for Brinell numbers greater than 175.

These formulas were used as a basis for the development of the formulas shown in section 2 above.

A fairly accurate, convenient, and easy to remember relationship is:

Tensile strength (lbs/in.^{2}) = 500 × Brinell number.

About the same time that the National Bureau was carrying on its investigations Alfred Heller[5] made a very complete study of conversion of hardness numbers between the C scale of the Rockwell tester and Brinell values and derived some very far-reaching conclusions, which may be summed up as follows: When steel hardens deep enough so that both Brinell and Rockwell impressions are well within the steel of uniform hardness, a single hardness conversion table can be used.

Heller's work showed that for the heat-treated steels studied (5 analyses of carbon tool steels with carbon content ranging from 0.35 to 1.30 per cent, 1 light alloy of chrome-vanadium steel, and 2 heavy alloy steels with carbon as high as 2.20 per cent) analyses had no effect on the Rockwell-Brinell conversion providing they have hardened uniformly throughout their section. This meant that for shallow-hardening steels Brinell tests must be made on sections thin enough to insure uniform hardness throughout, if correct Brinell surface-hardness readings are to be obtained.

Because conversion was used in a general way in connection with the Rockwell hardness tester, the Wilson Mechanical Instrument Co. made a study of all previous conversion work about 1930. They published a conversion chart now known as Wilson Chart #38, based principally on the work done at the Bureau of Standards and by Heller, as well as in their own Standardizing Laboratory insofar as C scale values were concerned. The B scale values were based on the work done at the Bureau and in their Standardizing Laboratory. The chart values have been adjusted slightly during the past 15 years but, generally speaking, few changes have been made. Additions of the 136° diamond pyramid hardness values were included. Well over 50,000 copies of this chart have been distributed and only an insignificant number of cases have developed where the values were in error, *provided* the precautions printed on each chart were observed.

Wilson Chart #38 is given in the Appendix. Particular attention is called to the wording, headings, limitations, and descriptive matter shown in this chart. A little later, when more recent work on conversion is discussed, a comparison should be made between values shown on Chart #38 and subsequently determined values. Practically perfect agreement will be found for all scale values, *especially in the range of* Rockwell C20 to C65.

Although numerous conversion charts appeared following Heller's work and that of the National Bureau of Standards, nothing was added to help clear up the wide discrepancies in conversion values, especially in the B scale, until about 1940. Important progress, however, was being made by R. Heyer, and his work on the "Analysis of the Brinell Hardness Test"[6] was later to play an important part in the study of conversion relationships.

About 1940, three groups, working independently but cooperating with each other, made valuable contributions to conversion relations. These were (1) the work at Westinghouse Research Laboratory by Howard Scott and T. H. Gray, (2) the work of Robert Heyer at the American Rolling Mill Co. and (3) the work of the Subcommittee on Indentation Hardness of American Society for Testing Materials Committee E-1 on Methods of Testing. This committee is largely responsible for the adoption of the same conversion values by the American Society of Testing Materials, the Society of Automotive Engineers and the American Society for Metals.

Scott and Gray's Work

Scott and Gray[7] found that reliable conversion relations between Rockwell numbers and diamond pyramid numbers could be obtained on heat-treated steels independently of composition. In addition to making tests on a large number of steel blocks of a wide range of compositions, quenched and tempered to various hardness values, their work included a mathematical study of the relation between 136° diamond pyramid hardness and Rockwell C scale values which was of value in studying the test results obtained. Extending their work to sintered carbides, these investigators found that the relation between tests made with the diamond Brale penetrator of the Rockwell tester and diamond pyramid hardness was dependent on the elastic modulus of the metal tested.

They presented a separate conversion table for sintered carbides, which have a very high elastic modulus (Fig. 75). This work was continued by Gray in a study of the relationship that existed for metals of lower hardness.[8] It was found that effects of the surface preparation of the softer metals must be considered. After investigating the effects of grinding, filing, and machining, it followed that grinding caused less superficial hardening than filing or machining. Consequently the samples used in the study of softer metals were lightly ground when necessary, and this was followed by rubbing with 00 emery paper.

After a thorough theoretical study and many experimental tests, Gray concluded that no discernible affect was due to elastic moduli for the metals studied—which varied from 2.5 × 10^6 to 60 × 10^6 pounds per square inch—except for Rockwell C Scale vs DPH or Brinell relationship.

This study may be summed up as follows. Conversion relations between Rockwell scales using the diamond Brale penetrator and diamond pyramid or Brinell hardness values require a separate table for metals of widely different moduli of elasticity, as for example one for tungsten carbide, one for steels and nickel alloys, and one for copper alloys. All these same metals may be grouped together in other conversion relationships not involving the use of the diamond Brale penetrator.

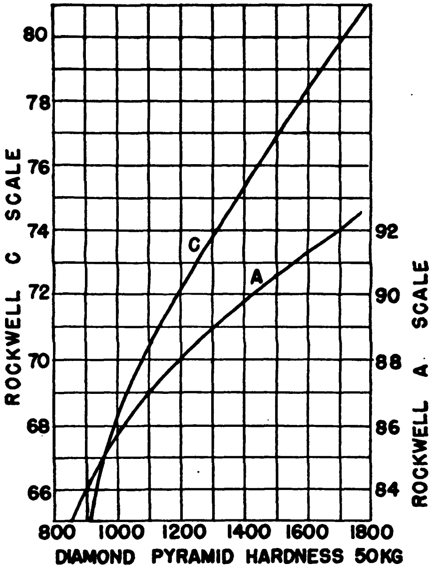


Figure 75. Conversion curves for sintered carbides (*by Scott and Gray*).

The lack of the effect of elastic modulus on the amount of elastic springback with tests made on the Rockwell scales using ball penetrators is probably due to the effect of lower stresses and more equitable stress distribution under the ball penetrator. As harder metals are tested, the effect of elastic recovery even with the 1/16-in. ball penetrator will become more pronounced due to flattening of the steel ball.

With the Rockwell C scale tests, the stress concentration under the tip of the diamond cone is high, and the elastic modulus is thus able to exercise its influence. More work on determining the influence of modulus of elasticity at low hardness values on conversion values between depth- and diameter-measuring instrument would be useful to confirm Gray's conclusions.

Heyer's Work

Robert H. Heyer[9] made a very complete study of the effect of the work-hardening capacity of a metal on conversion relationship. He showed, for metal softer than 240 Brinell, both ferrous and nonferrous, that a single conversion table will have large errors due to differences which may exist in the amount of cold-working prior to testing, as well as that which occurs during the test itself. So conclusive was Heyer's work that Wilson Chart #38 now contains the following statement.

> "The indentation hardness values measured on the various scales depend on the work-hardening behavior of the material during the test, and this in turn depends on the degree of previous cold-working of the material. The B-scale relationships in the table are based largely on annealed metals for the low values and on cold-worked metals for the higher values. Therefore, annealed metals of high B-scale hardness, such as austenitic stainless steels, nickel and high-nickel alloys, do not conform closely to these general tables. Neither do cold-worked metals of low B-scale hardness, such as aluminum and the softer alloys. Special correlations are needed for more exact relationships in these cases."

The extent to which hardness conversion of soft metals is dependent on the degree to which the material has been previously strain-hardened before test may be shown from values taken from Heyer's work. A cold-rolled aluminum alloy and annealed ingot iron have a Brinell hardness (500-kg load) of 66, whereas the Rockwell B Scale hardness is 7 and 31, respectively. Thus a conversion chart for the iron would have almost a 25 point B scale error for aluminum. On the other hand, some metals, such as brass and low-carbon sheet steels, have the same Rockwell and Brinell relationship.

Furthermore, Heyer shows that the dependence of conversion relationships on strain-hardening characteristics varies with the testing load. As the load is increased using the same size penetrator, the increased strain raises the hardness to a degree depending on the pretest capacity of the metal for strain-hardening. An annealed metal and a cold-worked metal having the same 15-T scale hardness on the Rockwell superficial tester will show different values when tested under the B scale of the normal tester. The annealed metal will be harder because of its additional capacity for cold-working. For soft metals having hardness levels considerably different from brass or low-carbon steels, specially prepared conversion charts are necessary other than those prepared from brass and steel samples, and this is one approach to the problem.

Upon examination of the impressions made on different materials, Heyer found that an indication of the state of strain-hardening of the metal could be obtained by the appearance of the indentations. This had also been noted in earlier work by Norbury and Samuel.[10] Soft annealed metals have "sinking" type contours, whereas cold-worked metals have "ridging" type indentations; between the annealed and heavily cold-worked condition flat contours are found.

When tests are made on different materials with the Rockwell B scale, F scale, 45-T scale, 30-T scale, and 15-T scale, and plotted according to the type of indentation contour as determined by Meyer, *n* curves result, as shown in Fig. 76. As these tests were made from different materials, it will be observed that the chemical composition is of no great consequence when comparison is made between all annealed materials, and between all metals in the strain-hardened conditions; that is, for each category a conversion relationship of fair reliability may be drawn. The solid lines in Fig. 76 are from Wilson Chart # 38.

It will be observed that this chart is satisfactory for "sinking" type impressions but inaccurate for "ridging" type impressions in the range of B0 to B50, and the reverse is true for values B50 to B100. This is logical, as the samples used in preparing Chart #38 in the low B range were chiefly annealed and half hard brass, and approached fully hardened materials in the B50 to B100 range.

Results similar to those shown in Fig. 76 are obtained if Rockwell values are compared with Brinell or diamond pyramid hardness values.

In the chapter on Meyer's analysis it was shown that the Meyer constant *n* represents work-hardening capacity, and methods for determining *n* were given. This method may be used for a quantitative measure of work-hardening capacity and thus facilitate the selection of the proper conversion relation, as it was shown that the Meyer constant *n* varies from about 2.50 for dead-soft annealed metals to slightly under 2.00 for metals in the cold-worked condition.

Additional Work

The joint A.S.M.–A.S.T.M.–S.A.E. Committee on Hardness Investigations functioning under the Section of Indentation Hardness of A.S.T.M. has prepared a conversion chart in the form of three tables for practically all constructional alloy steels and tool steels in the as-forged, annealed, normalized, and quenched and tempered conditions, provided they are homogeneous. This is published as A.S.T.M. Standard E 48–43T.

This committee has accomplished much toward establishing a standard conversion chart for heat-treated steels. It is hoped that its work will continue by preparing complete conversion charts by material classifications or by strain-hardening classifications.

A start has been made by the A.S.T.M. Committee on Indentation

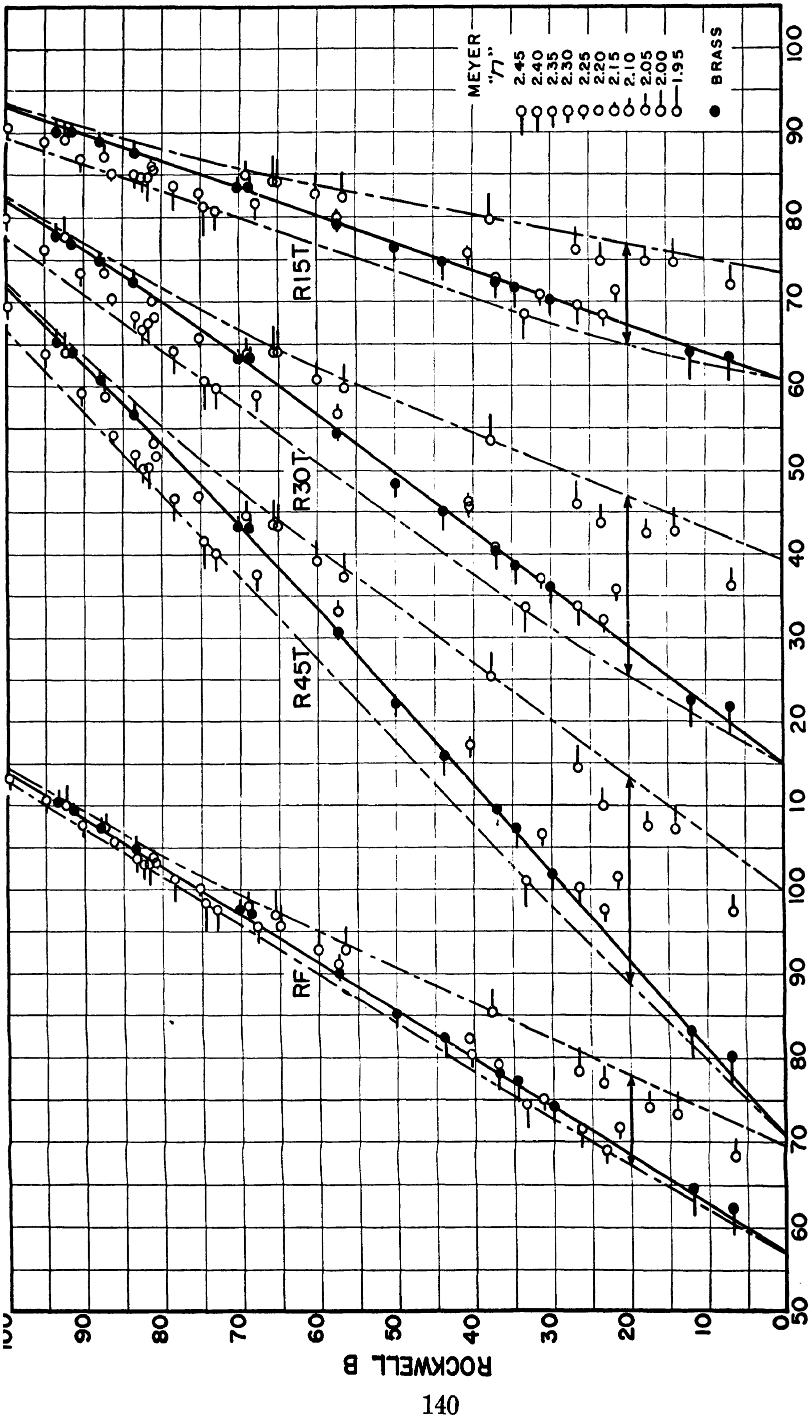


Figure 76. Conversion as determined by Meyer "*n*." (*From work of R. H. Heyer*)

Hardness in publishing Standard E 48–43T for conversion tables for steel. A.S.T.M. Standard E 33–42 covers standard hardness conversion tables for cartridge brass (see Appendix). From Heyer's work, charts according to material classification may be prepared for aluminum alloys and copper in the cold-worked state and also for 18–8 stainless steel.

H. P. Huston, Jr.,[11] presented a paper on hardness conversion values for nickel and high nickel alloys, which represents a very thorough study of conversion relationship for these metals. This chart is likewise shown in the Appendix. This work is another outstanding example of conversion relationships by material classification. Close examination shows good agreement with the Wilson Chart #38 and A.S.T.M. E 48–43, especially in the C-scale range.

Huston's work, as well as Scott and Gray's, presents the data in empirical equation form, but as most users of conversion prefer the use of tables such formulas are omitted from this text.

Likewise the comparisons between empirical and theoretical equations are omitted. These mathematical considerations are usually based on the assumption that the hardness number is the load divided by the indentation area. These considerations are valuable since they serve as a guide in determining empirical equations and indicate factors which introduce errors in conversion. The justification for omitting such mathematical considerations is that practically all conversation charts in use are based on actual tests and the theoretical study is made to explain anomalies.

The Scleroscope operates on such a widely different principle from static indentation testers that any conversion relationship developed would be only very approximate. Scott and Gray included the Scleroscope in their previously mentioned work.[7]

In summing up the discussion of conversion relationships it should be emphasized that conversion is useful in a general way. It should be used only when it is impossible to test the material under the conditions specified, and when resorted to it should be used with discretion and under controlled conditions. The hardness should be uniform to a depth of at least ten times the depth of indentation, and the tests should be made on properly prepared specimens on flat surfaces only.

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Chapter XI

Applicability of Hardness Tests

Hardness tests have tremendous applications in the metal-working industry, but in the final analysis the test is generally conducted to determine the suitability of a material to fulfill a certain purpose. Grading metals according to hardness, checking the uniformity of metals, relating hardness to some other physical property all have the same purpose. Is the material suitable for the purpose intended?

Most hardness tests are on a comparative basis. It really matters little if hardness does not represent one definite physical property; absolute hardness—if there were such a property—is not essential, as the engineer principally wants to be certain of a part having proper qualities for the intended purpose.

As hardness tests are generally on a comparative basis, there is no one hardness test which meets the optimum conditions for all applications. The choice of the proper test and testing equipment depends on many factors, such as size, shape and thickness of the test piece, composition and structure of the metal, surface conditions, quantity of work to be tested, accuracy requirements, hardness of the specimen, etc. Often a compromise may have to be made, for a hardness test which might satisfy one condition may not meet another. Furthermore, the economies of the problem must be considered, as for example the most desirable test as far as accuracy is concerned is likely to be too costly to perform on a 100 per cent production basis. Again, a test might be desired which could not be used because of the physical dimensions of the piece.

Hardness tests may be used for specification purposes as between buyer and seller. Standard specifications are often set up by technical societies such as the American Society for Testing Materials, American Society for Metals, Society of Automotive Engineers, etc. The tests may be made in the inspection department of one company to check incoming material, or to check the operations of one or more departments or the finished product. Tests are even made at various stages of the manufacture of the different parts that go into an automobile, washing machine, typewriter, machine tool, etc.

Because of the multiplicity of uses of the hardness test and the interrelations of values determined in different locations—the selection of the test being to a certain extent determined by convenience—it follows that the most important requisite of hardness testers is that they be so made as to give identical and reproducible values for the same material.

The greatest of care and the best judgment must be exercised in outlining hardness specifications. Too close limits place a hardship on the producer and may even be beyond the range of accuracy of the testing equipment. Too wide limits may result in an inferior product. The design engineer or the metallurgist must set the specifications, insofar as the physical requirements of the part are concerned. If the testing engineer finds the limits too close it may be necessary to provide for special calibrations of the testing equipment if readings taken on one machine are to be compared with those taken on another.

An example will illustrate the point in question. Let it be assumed that a certain part should have a Rockwell hardness of C55 to 60. In this hardness range Rockwell testers in good operating condition will agree to about ± 0.5 point. Thus on satisfactory material readings of from C54.5 to C60.5 may be obtained on machines in good calibration, but likewise material of C54.5 and C60.5 hardness may be accepted. To make certain that material C55 to 60 is being received, the specifications should be set at C55.5 to 59.5. Such limits would not cause too great a hardship for anyone.

Suppose, however, that the requirements are C60 to 62. To be certain of obtaining this value and making allowance for variations in machines, the specifications should be set at C60.5 to 61.5. Most assuredly this would inflict hardship on the heat-treating department. Under such conditions it would be preferable to determine the difference in readings between the two machines on which the parts were to be tested and to allow for the difference. This may require the producer and user to make a series of round robin tests, but this is preferable to setting specifications which are impossible to meet.

As softer material is tested, larger impressions result and generally a greater tolerance is required in the testing equipment. Likewise, softer material is less uniform; this makes the problem more difficult, as it requires a test block of uniform hardness to calibrate a tester of the depth-measuring design. Fortunately, the hardness limits used in specifications generally open up as softer material is tested; hence the variation from one machine to another is not of serious proportions.

Hardened and Tempered Steel

Probably the greatest single use to which the hardness test is put is in testing steel that has been hardened and tempered. For this purpose the C scale of the Rockwell tester is generally used, although in the laboratory the use of the 136° diamond pyramid test is common for research work.

It is well known that when carbon steel is heated to a high temperature and is cooled very rapidly it becomes hard; if it is cooled slowly, on the other hand, it will be soft. If the previously hardened steel is reheated at relatively low temperatures it is possible to impart to the steel any desired hardness over a wide range of values.

The first process is known as hardening, the second as annealing and the last as tempering. The above are not definitions of the processes, nor is this discussion intended to be a treatise on hardening and tempering of steel. Rather it is intended to show how the hardness test will differentiate between different values in steel which has been subjected to heat treatment.

Carbon is the most influential element in steel in determining the hardness obtainable by hardening. Fig. 77 shows the maximum hardness versus carbon content in carbon steels. These are the results obtained with the most rapid quenching, as in water, and the hardness test may thus be used to determine whether the optimum hardness has been obtained from a steel with a given carbon content. However it may not be desirable to use the steel in the maximum hardness "as-quenched" condition. By tempering the material other desirable properties may be obtained, though at the expense of hardness. This applies to all plain-

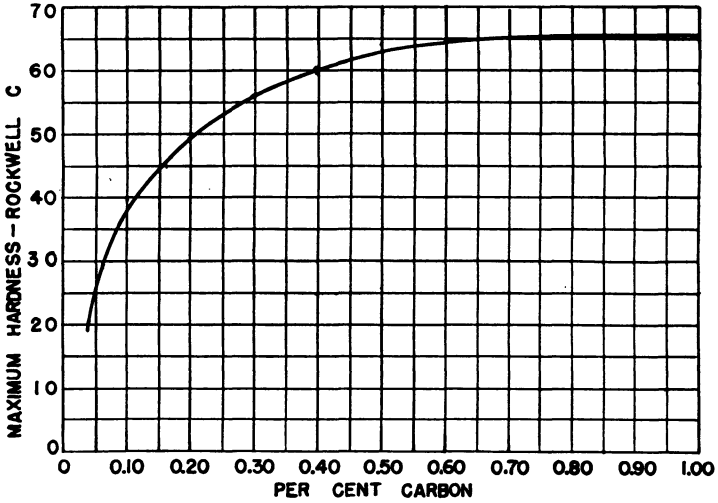

Figure 77. Maximum hardness versus carbon content.

carbon and most of the other commonly used steels. Fig. 78 shows the Rockwell C scale hardness of 45 carbon steel when tempered at different degrees of heat. Similar curves of hardness versus temperature are available for all commercial steels.

If a plain-carbon steel of sufficient mass is quenched in a medium which produces a less drastic quench than water, as is the case if oil is used, the hardness is very much less. In the case of the 45 carbon steel it would be about Rockwell C30.

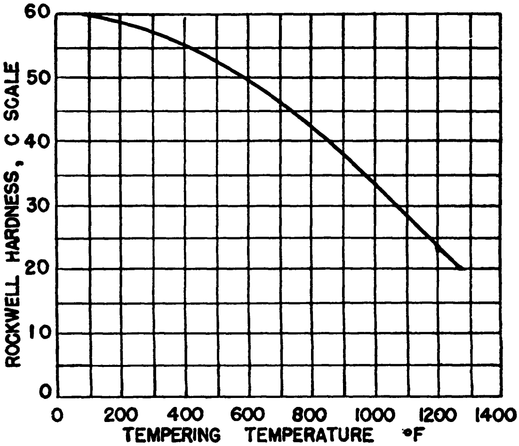

Figure 78. Hardness vs tempering temperature for 45 carbon steel.

Thus, in a plain-carbon steel the hardness test is extremely valuable in measuring and differentiating the hardness after heating and quenching in different media and after tempering at different temperatures. But there are many limitations to the use of plain-carbon steels. They are often alloyed, the metals most commonly used being nickel, chromium, tungsten, vanadium, manganese and molybdenum. Such steels are known as alloy steels. In their use, the hardness test is extremely important.

The purpose of alloying steel is to impart properties which plain-carbon steel does not have. Carbon steels are usually quenched rapidly in water for hardening and usually harden only to a depth $\frac{1}{16}$ to $\frac{1}{8}$ in., depending on the thickness; underneath this hardened layer will be a soft, tough core. Alloying the steel maintains the surface hardness and also carries the hardness to a much greater depth than for a plain-carbon steel. This is very important when work of large dimensions is hardened, as the depth of hardening is influenced by the size of the specimen. The degree or depth of hardening produced is not the same for all alloying elements, and the hardness test is used among other things to determine the depth hardness characteristics, generally referred to as "hardenability." It may be defined as the capacity of the steel to harden by quenching.

For years metallurgists have been devising special tests for measuring the hardenability of steel. Rapid advances have been made since 1938 when the Jominy end-quench test was introduced.[1] This is a simple and useful test, which permits hardenability data to be obtained over a wide range of sizes and also permits these data from various sources to be interchangeable. It is not generally suited for shallow hardening steels, such as plain-carbon steels, but is admirably suited to alloy steels except those to be heat-treated in very heavy sections.

In the Jominy end-quench hardenability test, the standard by which the hardenability is determined is the Rockwell C hardness at a given distance from the water-cooled end of the specimen, or the distance from the water-cooled end of the specimen at which a given hardness may be found. Briefly explained, the approved procedure for conducting and interpreting the test consists of machining or casting the samples to be tested to dimensions of 1 inch diameter and 4 inches long in the case of the preferred specimen. The sample is heated to proper temperature and quenched with a jet of water which comes in contact with the end of the sample only. This end of the sample is thus cooled very quickly and the opposite end very slowly. Rockwell C scale hardness tests are made at $\frac{1}{16}$ in. intervals from the quenched end along the length of the cooled specimen. From the hardness readings and their distance from the quenched end it is possible to determine the behavior of the steel at different quenching rates. Special fixtures are provided for supporting the specimen on the Rockwell tester and making the tests at the specified distances.

From the hardenability test much valuable information is obtained and under certain conditions it may be more useful than chemical analysis. It has proved to be of great value when medium-carbon alloy steels are considered. In such cases one alloy steel may be substituted for another, provided the two steels have equally good hardenability. The following information may be obtained from the hardenability test:

(1) Maximum hardness at a cooling rate of about 600° F. per sec.

(2) Depth of hardness.

(3) Effect of size or mass.

Hardenability values may also be determined for cast steels and thus an idea of the depth of section to which cast steel will harden may be obtained.

Just how does all of this tie in with everyday problems of hardness testing? Enough has been given to show that the hardness test may be used to determine differences in heat treatment of different steels. Experience has shown that, generally speaking, increasing the hardness increases the wear. Thus it is possible to specify definite hardness values for different tools, dies, and other heat-treated parts.

Certain types of tools, such as blacksmiths' tools, hammer dies and the like, may have comparatively low hardness values, whereas razors, engraving tools, etc., have high hardness values. In automotive work parts which have been hardened and tempered require hardness inspection. Such parts include steering arms, axle shafts, crankshafts and many others. This testing provides a check on the heat treatment to make certain that the specifications are being met; thus failure of the part in service is prevented. The percentage of the parts to be inspected depends on many factors which cannot be discussed here, as they are too involved. Sufficient inspection should be made to prevent the possibility of an improperly heat-treated part finding its way into a final assembly. King pins, valve tappets, gears, and camshafts are among the parts tested 100 per cent for hardness.

The advantages of the hardness test on heat-treated parts may be summarized in conclusion by pointing out that it provides a simple rapid, non-destructive test for checking the quality and uniformity of heat treatment.

The picture is probably best presented in an article published in *Machinery* (October, 1937) entitled "Selecting the Most Suitable Steel for Tools." This is reproduced in the Appendix, and it gives the characteristics required for different types of tools and the suitable Rockwell hardness when specified types of steel are used.

Case-hardened Steels

Hardness tests are very important in testing the hardness of case-hardened steels, as they provide information concerning the hardness and the depth of penetration of the case.

In testing case-hardened material, it is essential that the depth of case be sufficient to support the penetrator properly. The case depth should be at least ten times the depth of indentation. As the depth of indentation of a Rockwell C63 value is approximately 0.003 in., it is necessary that the case depth be about 0.030 in. if a true Rockwell C scale reading is to be obtained.

A low reading might indicate a soft surface or a shallow case depth. This feature is often used to advantage in controlling depth of case. A Rockwell A scale test is made and also a C scale test. If the C scale test is lower than the A scale value, when converted to the C scale, then it is safe to assume that the surface hardness is correct, but that the C scale value is in error due to insufficient depth of case. Correlations may thus be established for controlling the depth of case by the C scale value. Such control should be augmented by careful supervision of the chemistry of the steel and by accurate heat-treating in the case-hardening process.

Hardness penetration of the case may be studied by taper-grinding the sample with a slope of from 10 to 1 or 20 to 1. The test is then made on the surface below the original unground surface. The hardness values are reported and plotted against the depth in inches below the unground surface. In this manner the hardness gradient may be studied. Great care must be taken not to allow the grinding to affect the hardness. Curves obtained in this manner are similar in characteristics to those shown later for nitrided steel.

Incidently, the hardness of the core may be tested by grinding a depression in the piece depending upon the case depth, and measuring the hardness at the bottom of the depression.

Decarburization

Decarburization caused by loss of carbon from the surface of the steel during heating for forgings, annealing or hardening may be determined by the hardness test. It is important to detect and prevent decarburization, as it results in the loss of wear resistance at the surface. The test generally used for decarburization in heat-treated steel involves two determinations—one with the 15N scale of the Rockwell superficial test and one with the C scale of the normal Rockwell test. If the equivalent Rockwell hardness is not obtained by converting from the 15N scale to the C scale, a soft decarburized surface may be present. Decarburized surfaces 0.004 in. or deeper may be detected in this manner. The 136° diamond pyramid test may also be used for this purpose, just as it may be used to determine hardened case depths. Very thin decarburized layers may be detected only by the use of the microhardness test, which will be discussed later.

Nitrided and Thin Case-hardened Surfaces

If a case is hard, but only about 0.005 to 0.010 in. thick, it must be tested by either the Rockwell superficial method, the 136° diamond pyramid test, or the Monotron. Fig. 79 shows the depth-hardness characteristics on such hard, thin cases after taper-grinding, as explained previously. The samples were nitrided at constant temperatures for 12, 24 and 72 hours. These curves clearly show the different hardness gradations caused by the various periods in the nitriding process. It will be observed that with tests at a depth of 0.010 in., hardness values for the sample nitrided for 12 hours are practically the same as those for the core, but in the sample nitrided for 72 hours there is a considerable increase in hardness.

Surface hardness less than about 0.005 in. thick generally cannot be determined by the depth-measuring method, except possibly the Monotron, using a 3-division penetration. The Vickers tester with load of 1 to 5 kg, or the Tukon tester is used for measuring the hardness of such thin cases. When cases are in the neighborhood of 0.001 to 0.002 in. the microhardness tester is necessary.

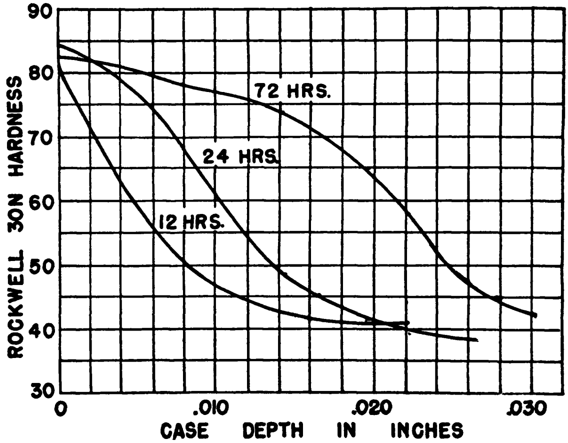

Figure 79. Depth hardness characteristics of steel nitrided at constant temperature for 12, 24 and 72 hours.

Forgings

Forgings are generally tested by the Brinell method. The large impression of the Brinell test is of distinct advantage because it results in an integrated value rather than a very local value, as would be obtained in a Rockwell test. Hence, a very close relation exists between Brinell hardness and tensile strength on forgings. Surface conditions such as decarburization on forgings, which are frequently not detrimental, do not appreciably affect the Brinell number.

Cast Iron

Cast iron is generally tested by the Brinell method, but the application is not as complete as in the case of forgings. The larger indentation of the Brinell test is an advantage because the material is not uniform and the Brinell indentation will produce a good average result. Any surface conditions, insofar as hardness is concerned, will be minimized by the deep indentation, it being necessary only to prepare the surface so that a well-defined impression results. In cast iron a good relation exists between tensile strength and Brinell hardness values. The most recent work on this subject was done by J. T. MacKenzie,[2] who shows that the relation between gray cast iron and tensile strength follows this deduction:

$$\text{Tensile} = 1.82\ (\text{B.H.N.})^{1.85}$$

Table 5 from MacKenzie's work shows the tensile strength versus Brinell diameter for diameters of impression from 3.20 to 5.80 mm. In all this work the 3,000-kg load was used. A statistical study which included well over a thousand determinations showed a correlation coefficient of 0.78 with a standard error of 18 per cent. The tests disclosed that section size had no effect on the Brinell tensile ratio; however, alloys which hardened the matrix lowered it.

Table 5. Expected Tensile Strength Calculated from Brinell Hardness Number

Tensile Strength = 1.82 $(\text{BHN})^{1.85}$ for Gray Cast Iron

Diameter mm.	BHN	Tensile Strength (psi.)
3.20	363	99 100
3.30	341	88 200
3.40	321	78 900
3.50	302	70 500
3.60	285	63 300
3.70	269	56 900
3.80	255	51 500
3.90	241	46 400
4.00	229	42 200
4.10	217	38 200
4.20	207	35 000
4.30	197	32 000
4.40	187	29 000
4.50	179	26 800
4.60	170	24 300
4.70	163	22 500
4.80	156	20 800
4.90	149	19 200
5.00	143	17 500
5.10	137	16 300
5.20	131	15 000
5.30	126	14 000
5.40	121	13 000
5.50	116	12 000
5.60	111	11 100
5.70	107	10 300
5.80	103	9 200

The Rockwell tester is used in testing cast iron, especially in small sections, where there is not sufficient area for a standard Brinell test.

The B scale is sometimes used but the E or K scale is preferable. The ⅛-in. ball, as in the E and K scales, gives a better average reading than the $1/16$-in. steel ball. The surface must be properly prepared, as the Rockwell test cannot be made on the surface as cast. It is also necessary to prepare the surface where the casting rests on the anvil to make certain that a firm support is provided.

To obtain correlations between Rockwell and Brinell values, it is usually advisable to take about 5 Rockwell readings and average them to compensate for the hardness variations in small areas as covered by the Rockwell penetrators. This is especially true when using the B scale and applies to a lesser degree with the E and K scales.

Very good Rockwell results are obtained with the Rockwell tester, using the E scale and removing sufficient metal from the surface of the casting to insure that the test is made in metal that is truly representative of the sample.

Hard white iron castings are generally tested on the C scale of the Rockwell tester, or by the 136° diamond pyramid method. If the material is not homogeneous, several readings should be taken and averaged.

Chilled iron rolls are generally tested for hardness by the Scleroscope. The use of ordinary charts to convert such values to Brinell will generally introduce discrepancies of considerable magnitude, and a special conversion for chilled iron should be developed if Brinell values must be used.

Cemented Carbides

Cemented carbides are generally tested with the A scale of the Rockwell tester, the 30N scale of the Rockwell superficial tester or by the 136° diamond pyramid method. The use of the C scale of the normal model of the Rockwell tester generally results in severe diamond breakage.

The A scale is probably the best for testing this type of material. Its drawback is lack of sensitivity; but as this type of material is very uniform, and as special carefully calibrated samples may be used to check the machines in this hardness range, the A scale is used with much success for control purposes.

The use of the 30N scale of the Rockwell superficial tester would give very good diamond life; however, the minor load impression of the Rockwell superficial tester is so shallow that a very good surface finish is required if satisfactory results are to be obtained. For laboratory purposes, the 136° diamond pyramid test is used. This requires a carefully prepared sample, but diamond breakage is high because of the sharp point of the diamond and the nature of the material.

In the manufacture of cemented carbides, the hardness test is used as a control of the manufacturing process. In the use of cemented carbides, the hardness test is used for a knowledge of hardness itself.

Powdered Metals

The Rockwell F, H, and 15T scales, Baby Brinell, and 136° diamond pyramid test are all used in testing powdered metals. Low hardness values are generally obtained because of the porosity of the material. As the density is increased the hardness improves. In powdered metal work the hardness test is used for research and development work, for process control, and even for testing finished products to a limited extent.

Many different methods of testing hardness are frequently used. Also, many factors influence the results, especially porosity. These factors, together with the absence of data correlating performance with hardness values, have retarded the development of hardness testing of powdered metals.

Significance of the Hardness Test

Before going on to describe the use of the hardness test in the very important field of sheet metal, it might be well to consider at this time just what the hardness test evaluates, particularly in testing the materials just discussed.

It has been pointed out that steel is brought to its best condition for performance in a particular application by heat treatment. Later it will be shown that sheet metal is brought to proper condition by cold work. Sometimes a combination of both is used. Such treatments result in a change of hardness, and once the proper hardness limits are established it is possible to use the hardness test for inspection and control purposes.

The tensile test, in many cases, is used as a criterion of proper quality for best performance, for example in forgings, cast iron, low-alloy steel, and annealed carbon and alloy steels. For such materials there is a satisfactory relationship between the hardness test and the tensile test. In ferrous materials, the hardness vs. tensile relationship may be determined within a possible error of ± 10 per cent.

Shallow penetration tests permit the investigation and control of surface conditions, such as superficially hardened surfaces and decarburized surfaces.

If the hardness test is extended beyond the foregoing general uses, great care must be exercised and many factors taken into consideration in the use of the test. Under certain prescribed conditions the field of hardness testing may be extended to control of machinability, wear resistance, fatigue strength, toughness, etc. Considerable work has been done in an attempt to correlate hardness, usually in Brinell numbers, with machinability. Generally, the rule followed was that high Brinell hardnesses required low machinery speeds and *vice versa*. Recent work[3] shows that this is not always true. There are so many variables influencing machineability that no general conclusions can be drawn.

For any specific operation, as for example rough turning, the hardness test may be used as an index for any one steel, but beyond that it would be inadvisable to rely upon it too heavily. A new approach to this problem has been made in connection with microhardness and the use of Meyer's Analysis; this is referred to in the chapter on Microhardness Testing.

Wear resistance is generally examined by some form of wear test, which usually consists of a rotating disc against the surface of which the test piece is pressed under certain predetermined pressures. The loss of weight of the test piece in a given length of time is an index of the wear resistance.

Hardness tests do not provide a reliable index for the evaluation of wear, except where the results are compared for metals of the same composition. Under such conditions the greater the hardness the more resistant the metal to wear.

The same conditions prevail in the relation between hardness and toughness. A separate relationship must be determined for each metal. It might be added, however, that instruments designed to measure toughness, such as the Charpy, Izod, and torsion impact tests, indicate that toughness increases as hardness decreases.

A fairly consistent relationship exists between hardness and fatigue strength provided the structure and previous treatment of the steel are controlled. Surface finish, homogeneity of structure and other factors so influence this relationship that it is not advisable to place too much reliability on such curves, unless they have been checked for the particular application in mind.

One further use of the hardness test should be mentioned. It is often used in conjunction with the microscope to correlate metal structure with hardness. It provides a clue to help the metallographer interpret results, so that a much clearer picture is obtained than with the microscope alone.

Sheet Material

A separate chapter is devoted to the proper methods and limitations of the hardness test insofar as sheet material is concerned, but the suitability of the hardness test as a means of determining the quality of sheet material will be discussed here.

The tensile test is widely used for metals because it indicates modulus of elasticity or stiffness, strength and ductility. In most structural applications the property of tensile or yield strength is an essential one. Sheet metal has many applications; sometimes the tensile properties must be known. In testing sheet material for deep-drawing applications the tensile test is generally preferred for quality control, but this test is costly and time-consuming. Hence hardness tests may be substituted for tension tests because they are easy to make and do not destroy the material.

As far as it is possible to describe the testing of sheet metal in a few words, it may be done as follows. Sheet metal is generally tested for its drawing and stamping qualities. Within reasonable accuracy the Rockwell test is an indication of tensile strength. The 136° diamond pyramid test may also be used for this type of testing, but the speed of the Rockwell tester has brought about its universal use. The cupping test will give an indication of the depth of draw. Thus to know whether a metal will work in a die only the hardness test and the ductility test are essential, and it is the experience of testing engineers that if only one test can be made it should be the hardness test.

Cold-rolled strip steel is produced in various grades or tempers, each of which is suitable for certain special types of work. Hardness limits may be set for each temper, usually in the Rockwell B or 30-T (Rockwell superficial tester) scales, depending on the thickness. The following table shows the values generally used for the B scale for different tempers of mild steel.

Rockwell B Scale	
#1 Hard	90 ± 5
#2 Half-hard	80 ± 5
#3 Quarter-hard	70 ± 5
#4 Soft	60 ± 6
#5 Dead soft	45 ± 7

These values are used for information purposes only. If material is to be rejected the tensile test should be used to affirm the hardness values. Cup tests, grain-size determination and bend tests provide additional data.

Much study must be given to the selection of suitable steel for drawing purposes, and the proper condition of the die is important. Much information has been published on the subject of selecting proper sheet steel. It is by no means as simple as making a few determinations with a hardness test or even a ductility and tensile test or grain-size determination.

Sheet metal is used under various conditions, which include both steel and nonferrous metals for airplane construction and other structural uses and also flat panels for metal furniture and signs which have to be rather stiff and rigid, as well as deep-drawing applications which require ductility. So many factors enter into these applications that no one test or sometimes even a number of tests in combination suffice to predict the performance of the material in its intended use. However, when other variables can be controlled, it often happens that a determination of hardness alone will give a valuable indication of the performance of the material.

The hardness test plays an important part in the control of hardened and tempered steel used for springs. Such material is from 0.005 to 0.065 in. thick; it is heat-treated to obtain the desired physical properties, which are generally determined by C scale testing on the Rockwell tester. In the case of very thin spring material (0.005 to 0.030 in.) the 15N or 30N scale of the Rockwell superficial tester is used. This material can also be tested by the 136° diamond pyramid method. Material less ahan 0.005 in. must be tested by the method described in the chapter on Microhardness.

The hardness test in this case is used as a measure of the hardness of the thin steel in the "as quenched" condition, or as a measure of the temper.

Safety-razor blades are generally tested for hardness after hardening on the Rockwell superficial tester or by the 136° diamond pyramid method. In the case of the former, the 15N or 30N scales are used. On 0.004-in. steel blades only the 15N scale is used, and these readings are subject to anvil effect.

When using the 136° diamond pyramid test, the 5-kg load is used for blades 0.006 in. thick and heavier, and the 3-kg is recommended for blades 0.004 in. thick; actually the latter should be checked for hardness by the diamond pyramid method if accuracy and sensitivity are to be obtained.

Sheet brass is used to a considerable extent; its important physical characteristics are strength, wear resistance, spring properties and ductility. It is considered that sheet brass is adequately controlled if the chemical composition, hardness, ductility and, in the case of annealed material, grain size are within the required limits.

The basis for the use of the hardness test in connection with sheet brass may be found in two excellent papers[4, 5] presented at the American Society of Testing Materials Annual Conventions in 1929 and 1927.

As a result of this work and the continued activities of Committee B-5 of the A.S.T.M. on Copper and Copper Alloys, Cast and Wrought, the matter of hardness determination of sheet brass and other copper-base alloys has been greatly simplified and standardized, so much so that no other material has been so well studied and the results so nicely tabulated as those obtained on these particular nonferrous sheets.

A.S.T.M. specifications on copper-base alloys recommend the use of the B and F scales of the normal model Rockwell tester for materials 0.020 in. or more. The Rockwell superficial tester is recommended for 0.012 in. and heavier sheets.

It should be noted that in these specifications the hardness values are indicative of the tensile strength of all tempers of rolled brass sheet and strip and all hardness tests are subject to confirmation by tension tests.

The hardness test is used as a control of heat treatment of sheet aluminum alloys and also as a means of distinguishing various tempers and alloys. The use of the hardness test in sheet aluminum alloys has not been as general as in the case of brass and steel. There are two reasons for this. The first is that it has not been proved conclusively that the hardness test can accurately evaluate the degree of precipitation in this form of hardening. Secondly, aluminum-clad alloys contain a layer of soft material which renders the material non-homogeneous.

In the aviation industry where considerable sheet aluminum is used, the Rockwell tester is of invaluable aid. Generally 100 per cent of heat-treated sheet aluminum or aluminum alloys is checked for hardness. The high-strength aluminum alloys are checked on the B scale and soft and thinner gauges on either the F or E scales.

Sheet aluminum, therefore, is tested for hardness as a means of distinguishing between cold-worked or heat-treated materials and annealed materials. Hardness values are also used as an indication of the strength developed by heat-treating.

The Rockwell superficial tester and the 136° diamond pyramid test are used on thin gauges; extremely thin gauges are tested with the Barcol Impressor and the Webster hardness gauge.

The Rockwell tensile relationship is found to be very satisfactory for aluminum alloys such as 17 and 24. In "Alclad" materials the relationship has been found satisfactory in the case of heavier gauges, which may be tested with the B or E scale of the normal Rockwell tester. Apparently in such cases the minor load just penetrates the pure aluminum coating and a good relationship results.

Sheet zinc may be tested for hardness, and as this material will flow as the testing load is applied it is essential that the length of time for applying the load be carefully controlled. The Rockwell and Rockwell superficial testers are used for testing zinc in sheet forms; because of its characteristic of flowing under load, the major load is usually applied for 15 seconds. It is not necessary, however, to apply a time factor to the minor load or to use a time factor after the removal of the major load. The time factor for the major load begins when the mechanism for applying the major load is tripped, and the cycle ends when the handle for removing the major load is brought back to starting position.

Sheet zinc down to ⅛ in. may be tested with the E scale of the normal Rockwell tester; sheet zinc down to about 0.050 in. may be tested with the H scale. These values are for zinc in the soft condition. Thinner sheets may be tested if the zinc is hard. For thinner sheets the 30T or 15T scales of the Rockwell superficial tester may be used.

Tin plate is generally tested on the Rockwell superficial hardness tester using the 30T scale (1/16-in. ball penetrator and 30-kg load). This scale follows the recommendations of the Technical Committee on Tin Plate, Terne Plate and Black Plate of the American Iron and Steel Institute. This is the scale recommended by the committee for the hardness testing of all tin mill products in all gauges, base weights and tempers. As some of the thinner material may show anvil effect, the Committee further stipulates the use of the diamond spot anvil for supporting the material while being tested.

By no means is it to be assumed that the foregoing is intended to describe all the fields covered by the hardness test, or that the work cited is intended to represent completely all phases of the particular application. Rather, a limited number of examples are given to show the wide adaptability of the hardness test as it relates to the quality and physical characteristics of different materials.

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Chapter XII

Tests on Sheet Metal

The hardness test is widely used in testing sheet and strip metals and the results of the hardness test are of considerable value in conjunction with other tests in estimating the suitability of a metal for deep-drawing. It necessarily follows that it is highly desirable to know the thickness limits within which test results are sufficiently accurate. Several variables are encountered; these depend on the type and character of the metal tested as well as the test method used, *i.e.*, whether Brinell, Rockwell, Sceleroscope, or 136° diamond pyramid method.

Brinell Method

Because of the heavy loads used in the Brinell test, it is not suitable for testing sheet metal in its usual commercial thicknesses. The early specifications agreed in the limiting thickness for a satisfactory test and both the A.S.T.M. specification E 10–27 and British Standards Institute #240 (Part I) 1937 indicated that the thickness of the specimen should be at least 10 times the depth of the impression. The A.S.T.M. also specifies the limiting thickness as being such that no bulge or other markings showing the effect of the load should appear on the side of the piece opposite the impression. This is sometimes very difficult to determine.

The British specification of 10 times the depth of the impression is qualified by a statement that this value may be unnecessarily high, and in some instances lower values of the ratio may be permitted.

The depth of the impression may be calculated from the formula

$$\text{Depth of impression (mm)} = \frac{L}{\pi D H}$$

where L = Load in kg
D = Diameter of ball in mm
H = Brinell hardness number.

Other investigators found that this factor of 10 was not a general one, and G. A. Hankin and C. W. Aldous[1] conclude that the limiting value of the ratio may vary from about 6 for mild steel to more than 20 for hardened spring steel.

Research Paper 903 of the National Bureau of Standards[2] reports the limiting thickness to vary from 0.08 to 0.32 in., and concludes that a limiting thickness of 0.4 in. may be considered satisfactory for a true Brinell number with a load of 3,000 kg and 10-mm diameter steel ball. This investigation states further that it is safe to assume that the absence of a visible spot on the under surface of the specimen indicates that the thickness of the specimen exceeds the critical thickness.

R. H. Heyer[3] showed by direct measurements of plastic deformation in thick hardness test specimens that the depth to which permanent distortion could be measured varies with the type of impression. For a given diameter of indentation the depth of penetration for a "ridging" type impression may be only half that of a "sinking" type impression. This indicates that for cold-worked materials with ridging type impressions, and a low Meyer *n* constant, the thickness tested in the Brinell test may be considerably less than for annealed materials having sinking type impressions and high Meyer *n* constants. Note that this is based on a given diameter of indentation or a given Brinell value, provided the test load is not changed.

This work was not carried far enough to establish thickness ratios for materials and various Meyer *n* values. The thickness ratio of 10 is probably safe for most testing, and when ridging type impressions are encountered the safe ratio may be reduced somewhat.

Scleroscope

The problem of testing thin sheet on the Scleroscope is very complex and the height of rebound of the hammer is generally influenced when the specimens are less than 0.25 in. The mass of sheet specimens is generally so small that the sample does not have sufficient inertia to resist the kinetic force of the falling hammer so as to render the height of the rebound independent of the mode of support. In this case the type of support and material from which the support is made will influence the readings. Comparable values may be obtained on similar materials of the same mass if supported exactly in the same manner.

Very thin and soft materials will give much higher reading when they are supported on a hard steel anvil. When more than one thickness of the sample is tested the correct reading may or may not be obtained depending on the flatness, thickness, surface conditions, hardness and number of thicknesses tested.

If thin samples are tested on the Scleroscope all conditions of the test should be adequately controlled if duplicate results are to be obtained.

Rockwell and Rockwell Superficial Method

More sheet metal is tested for hardness on the Rockwell hardness tester than by any other method. The limiting thickness of material that may be tested on the Rockwell tester and Rockwell superficial tester without anvil effect is specified in A.S.T.M. specification E 18–42. This requires that the piece be of such a thickness that no bulge or other marking showing the effect of the load appears on the surface of the piece opposite the impression. The actual thickness to meet this requirement depends on the nature of the material.

In some cases it has been found that even though the impression shows through slightly, the Rockwell value may not be affected but to be absolutely certain of accurate results, lower limits of thickness should not be set.

On the other hand many specifications have been set permitting minimum thickness less than the above requirement and these have been used for many years and have proven very satisfactory for certain comparative purposes.

For example A.S.T.M. specification B 36–46T for brass sheet and strip gives Rockwell B scale values on nonferrous sheet down to 0.020 in. for inspection purposes. As this specification is intended as a substitute for the tension test and is principally concerned with a good correlation rather than accurate hardness values, these values are satisfactory.

The same specifications also give Rockwell superficial values for even thinner materials using the 30T Scale for sheets 0.012 in. in thickness. In using the Rockwell superficial tester a limiting value will eventually be reached where anvil effect is present even with such light load testing as 15 or 30 kg.

The minimum thickness that can be tested with the superficial tester may be decreased by use of a diamond spot anvil. This offers a highly polished plane surface as a support. It also provides more uniform frictional effect of the anvil as the metal of the sheet flows laterally under test. It is important that the type of anvil for testing thin sheets be designated in the specifications as different values may be obtained when thin metal is supported on the diamond spot anvil rather than on a steel anvil if anvil effect is present. Even for relatively thick sheets a difference may be observed between readings taken with steel and diamond anvils.

The diamond spot anvil is never used with the heavier loads of the normal model of the Rockwell tester as under such conditions its life would not be long and frequent breakage of the diamond would make the test uneconomical. Neither should the diamond spot anvil be used if the material is tested with the diamond N Brale penetrator of the superficial tester. The piece under test might break and thus cause damage to both the diamond anvil and diamond penetrator.

R. L. Kenyon[4] in a very complete study of the effect of thickness on the accuracy of Rockwell hardness tests on thin sheets has contributed considerable information on this subject. He worked with low-carbon killed steel but the many factors affecting the Rockwell readings would be the same in other thin metals such as hardened strip steel used for springs and nonferrous metals.

Preliminary tests were made to determine that the specimens were of uniform composition and structure throughout their thickness. Variation in thickness was obtained by etching in acid and careful polishing. It was found that the appearance of a bulge under an impression on a polished specimen was evidence that such a reading was questionable. Kenyon encountered considerable difficulty in determining when the bulge first appeared and when it was safe to say that a bulge was present or not. It was indicated that when the bulge was barely visible the reading was reliable. Therefore, he decided on a practical limiting thickness as being a deviation of two Rockwell numbers from the correct Rockwell number.

Some of the anomalies formerly found in testing sheets were clarified by this study; apparently the three following factors influence Rockwell hardness readings on thin sheets:

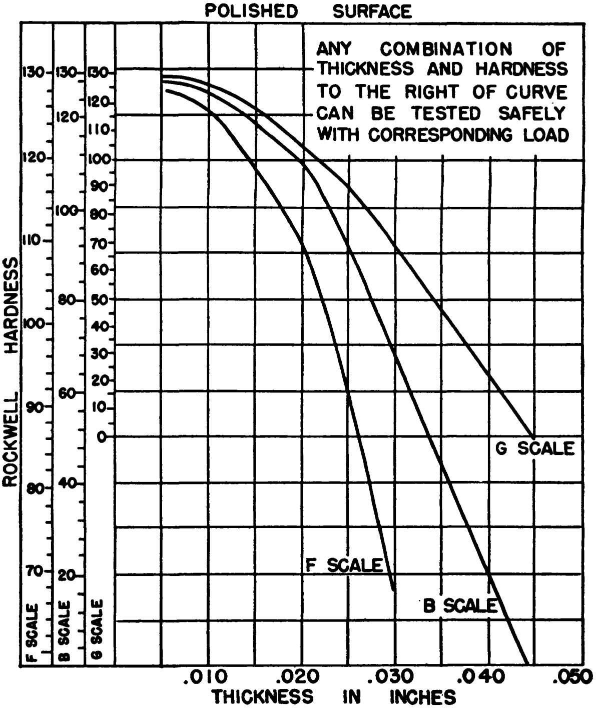
(1) Side flow: This causes low readings.
(2) Anvil effect: This causes high readings.
(3) Crushing- or punching-through effect: This causes low readings.

The intensity of these effects will vary with thickness and the reading obtained is the net result of all three superimposed on the true hardness of the material. Thus it is possible as thinner metal is tested to obtain first lower readings due to side flow and then higher readings as the anvil effect increases; this flow effect may be entirely offset by the anvil effect at some lesser thickness. This causes confusion because metal slightly thicker may give low readings and furthermore it is possible to obtain a correct value even when a definite bulge is observed.

Because of this lateral flow under the ball, the condition of the underneath surface of the specimen and the condition of the top surface of the anvil are important. A rough ground spot anvil will give a different reading than a highly polished steel anvil on testing thin sheets with anvil effect present. Likewise there may be a difference between readings when a diamond spot anvil or a steel spot anvil is used because of frictional effects as flow occurs. If the underneath surface of the metal is polished it may cause more flow with a resultant different reading. Polished anvils which become rough due to use may give a different reading.

Kenyon studied the effect of surface preparation by making tests on both polished and etched specimens. Different thicknesses were found to be required for limiting values for each type of surface. A greater limiting thickness was required for etched surfaces than for polished surfaces, probably due to flow of the metal into the cavities and pits on the roughened surface.

This work also showed that the ridge around the spherical impression changed to a depression at a certain thickness of the specimen.



(*From R. L. Kenyon's work*)

Figure 80. Limiting thickness of polished materials which may be tested on the B, F and G scales.

Heyer's[3] conclusions relative to the influence of "ridging" or "sinking" impressions in connection with establishing limiting thickness of samples for Brinell testing probably are applicable to the Rockwell method. An analysis of Kenyon's data shows that the limiting ratio of thickness to depth of impression varied considerably; in some cases it was as low as 6 and in other cases being over 10.

As Kenyon's work was summarized in terms of depth of indentation it is possible to determine the limiting thickness of materials for different scales of the Rockwell and Rockwell superficial tests. This work was on low-carbon steels so these values should be used only for materials of similar hardness and type of impressions. For example, the following curves will show appreciable error for most aluminum alloys. Fig. 80 shows the limiting thickness of polished surface for the B, F, and G scales of the normal Rockwell tester and Fig. 81 gives these results for the 15T, 30T and 45T scales for the Rockwell superficial hardness tester.

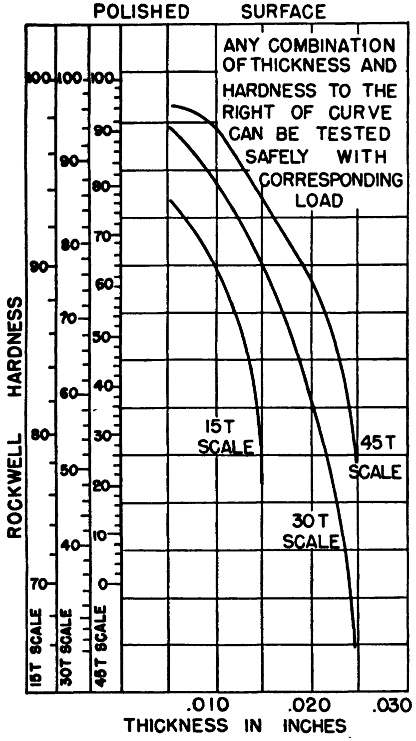


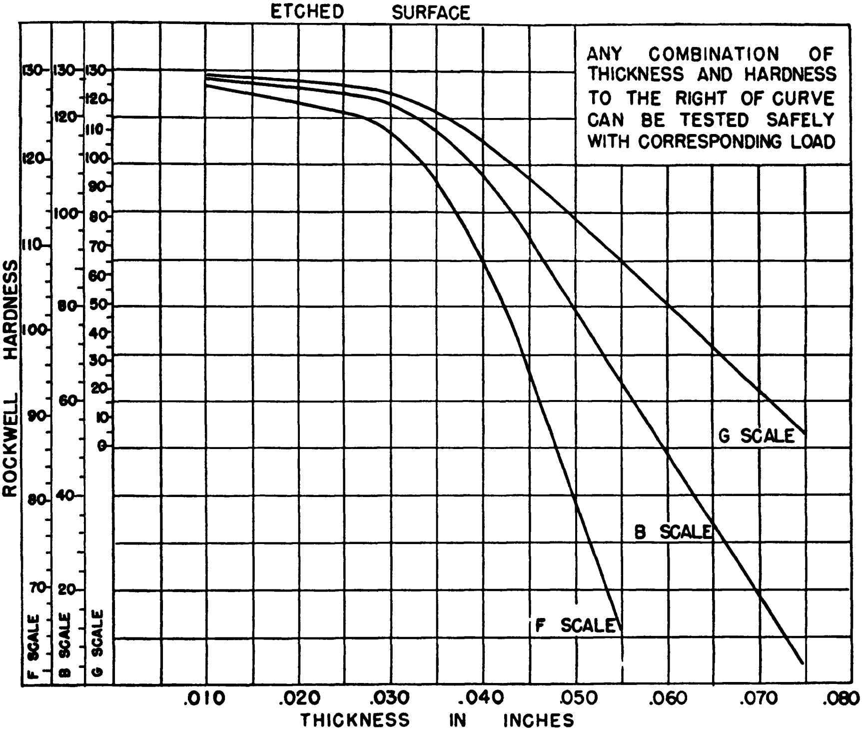
Figure 81. Limiting thickness of polished materials which may be tested on 15T, 30T and 45T scales.

(*From R. L. Kenyon's work*)

Figs. 82 and 83 give similar curves for the scales on etched surfaces. These curves are based on a deviation of two points on the various Rockwell scales from the true value.

Similar investigations on strip steel of various thicknesses from 0.005 in. to 0.070 in., hardened and tempered to Rockwell C scale values of 20 to 65 give a similar set of curves for heat-treated steels. These are shown in Fig. 84 for the normal model Rockwell tester and in Fig. 85 for the superficial model.

As this material was more uniform in hardness than the material investigated by Kenyon and as 1 point of Rockwell C scale hardness is of considerable importance in the range of Rockwell C50 to 65, the deviation was based on 0.5 point rather than 2 points. These data were obtained on a sample of 1.01 per cent carbon steel rolled from the same heat and carefully prepared in all operations. Experience has shown that these values hold fairly well for all metals tested on the C scale or its equivalent based on depth of indentation.



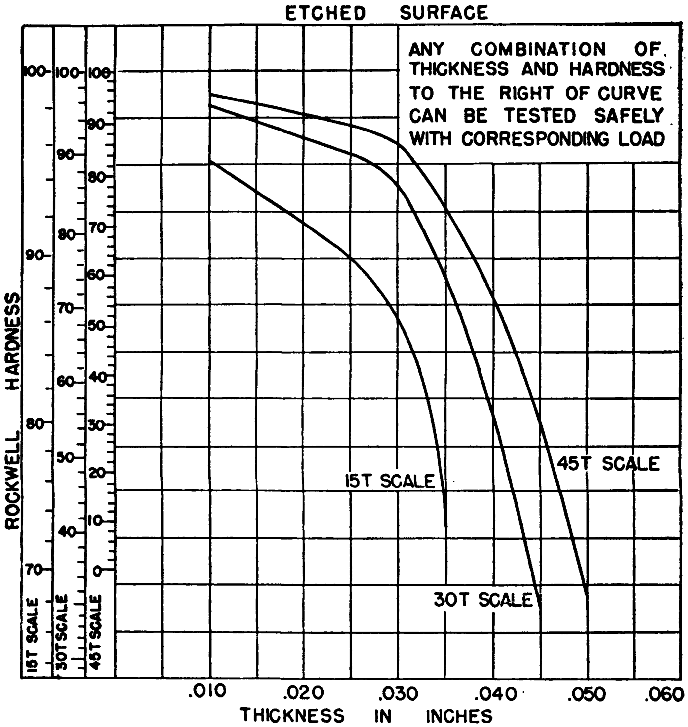
ANY COMBINATION OF THICKNESS AND HARDNESS TO THE RIGHT OF CURVE CAN BE TESTED SAFELY WITH CORRESPONDING LOAD

(From R. L. Kenyon's work)

Figure 82. Limiting thickness of rough (etched) materials which may be tested on the B, F and G scales.

As most thin heat-treated materials are tested in the polished conditions, these tests were not repeated on etched or rough surfaces.

An entirely different approach to this problem is suggested by the work of R. L. Peek and W. E. Ingerson who conclude that variations of hardness with depth may be detected by making measurements with different ball diameters in the same range of values of differential depth of indentation divided by ball diameter. Failure of the points to lie on a common curve is an indication of a variation of hardness with depth.



(From R. L. Kenyon's work)

Figure 83. Limiting thickness of rough (etched) materials which may be tested on the 15T, 30T and 45T scales.

In the case of sheet metal of uniform hardness such an indication would be the beginning of anvil effect. This method would probably be sensitive to one or two Rockwell numbers.

In conclusion, it should be emphasized that for Rockwell testing of sheet metals the lightest load possible consistent with good sensitivity and surface condition should be used. The minor load of the normal Rockwell tester penetrates to a much greater degree than the minor load of the superficial model and, oftentimes where it may be desirable to use the Rockwell superficial tester because of the light major load, a greater error might be introduced in the use of the superficial tester because of surface characteristics of the specimen. Rough surfaces, skin effect caused by rolling and other factors may introduce appreciable error in Rockwell superficial reading.

Under such conditions all influencing factors must be studied before a decision may be made and the final selection may have to be a compromise.

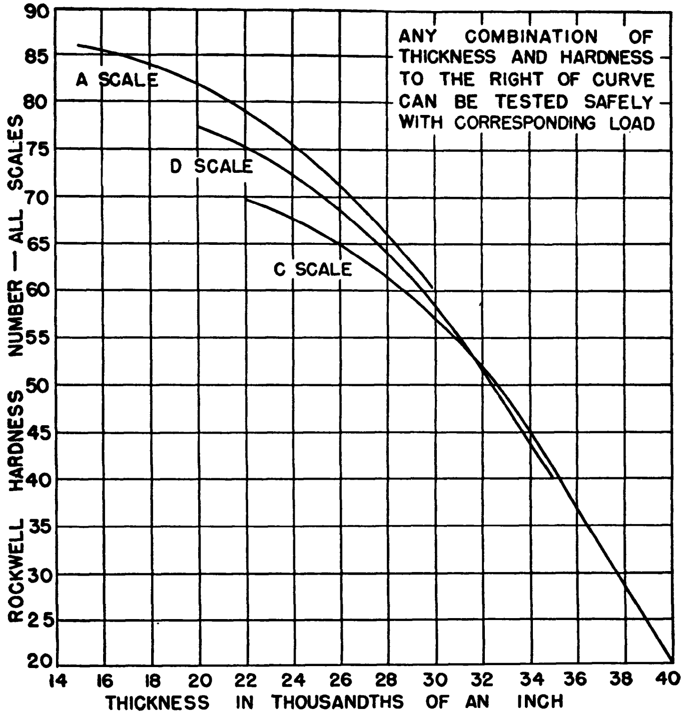


Figure 84. Limiting thickness of hardened and tempered steels which may be tested on the C, D and A scales.

Remember the following precautions in testing sheet metal with the Rockwell tester:

(1) Be certain the surface condition of the anvil is good. Rough surfaces or pits or impressions in the anvil will introduce errors.

(2) Never use the flat anvil in testing sheets.

(3) If the diamond spot anvil is used be sure to so specify in report of results.

(4) If the top or underneath surface is polished, this fact should be noted. Satisfactory surface finish may usually be obtained by rubbing on 0 or 00 emery paper.

(5) All Rockwell hardness tests on sheet metals must be made on a single thickness of the material. The use of additional thicknesses of the same material does not give the same effect as a solid piece of the same total thickness as the combined pieces. Lack of flatness of the samples and various degrees of flow of the metal on the surfaces between the different pieces cause this source of error.

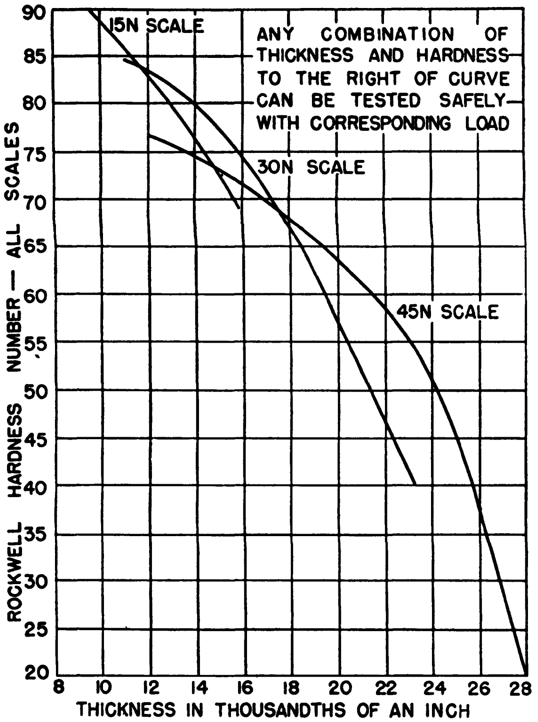


Figure 85. Limiting thickness of hardened and tempered steels which may be tested on the 15N, 30N and 45N scales.

136° Diamond Pyramid Hardness Method

The British Standards Institution #427:1931 requires that the thickness of the test specimen be at least 1½ times the diagonal of the impression for the diamond pyramid test. Hankins and Aldous[1] came to the same conclusion as a result of tests they completed. They stated: "In carrying out diamond pyramid hardness tests on thin samples a limiting value of the ratio of test-sample thickness to impression diagonal of 1½ gives results which are practically independent of test sample thickness for a number of ferrous and nonferrous metals. For tests on soft copper and soft brass sheet, however, a higher value of the ratio is necessary if accurate results are required."

It should be noted that in the same investigation it was not possible to determine a general limiting value of the ratio of thickness to impression depth for the Brinell test.

This factor of limiting ratio of test thickness to diagonal of impression of 1½ gives an error of about 3 per cent for mild steel and 10 per cent for soft brass and copper. It represents a ratio of impression depth to thickness of sample of 10:1.

In making the diamond pyramid test it is essential that the sheets are flat and in good contact with the supporting anvil. The supporting anvil must be in good condition, *i.e.*, free from pits and irregularities.

An additional factor which has been recently studied by Thomas B. Crow and John F. Hinsley[5] requires consideration. They confirmed that if indentations are made on heavily rolled strip so positioned under the diamond that one diagonal is parallel to the direction of rolling, an appreciable difference in diagonal length makes it inadvisable to rely on the measurement of only one diagonal. British Standards Institute #427 requires the use of the mean of the two diagonal readings and this is very necessary.

Placing the test-piece so that its direction of rolling is at 45° to the diagonal will give diagonal lengths which are practically equal.

The authors also considered the effect of bulge which occurs in "ridging" type impressions in the diamond pyramid test and prepared a corrected hardness table based on a formula which took into account the bulge area.

It was shown that the difference between hardness numbers corrected for bulge area and those not so corrected for bulge area may be of the order of 10 to 20 per cent. This correction which is a mathematical one may apply to some extent to all indentations having "ridging" type of impressions, but it is probably most significant in heavily cold-rolled strip and becomes of smaller proportions in other materials as ridging is most severe in such cold-worked sheet metal.

Crow and Hinsley's work would seem to justify the conclusion that specifications or standards should state how the bulge should be considered in the determination of the diamond pyramid number of cold-rolled materials.

A similar study should be made of "sinking" type indentations with concavity effects.

This in turn all reverts to the work of Heyer, beginning with his study of the Brinell test and followed by his study of the effects of "ridging" and "sinking" type impressions as they occur in all indentation tests. Heyer[3] has shown that the change from a ridging- to a sinking-type impression in the Brinell test occurs at about 2.25 to 2.30 for the Meyer constant n.

More work must be done along this line before all the answers are available. What is the effect of "sinking" and "ridging" type impressions on the diamond pyramid hardness number other than the area effect which may be calculated approximately? Does the law of geometrically similar indentations follow for "ridging"- and "sinking"-type indentations or only for flat type?

When the answers to these and other questions are found the matter of hardness testing of sheet metal insofar as limiting thickness is concerned may be simplified.

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Chapter XIII

Cylindrical Surfaces

When testing cylindrical surfaces, the results may be in error due to the curvature of the specimen. The differences between the reading on a flat material and a round material will depend on the applied load, the size and shape of indentation and the diameter and hardness of the specimen.

For control and specification purposes, if the diameter of the specimen being tested, together with load and penetrator used, are specified, there will be sufficient information available for duplication of results and generally this is all that is necessary. Or if a flat is prepared on the surface of the specimen where the test is to be made, this fact should be noted and again results will be in agreement if both parties prepare the flat in the same manner. This procedure has the disadvantages that the hardness of the specimen may be changed in preparing the flat, or the material may not be homogeneous in hardness, and the test would indicate different values at different depths. Furthermore, such pieces are rendered useless after being milled, filed or ground.

As the results are comparative for any one diameter of specimen under a given condition of load and penetrator, it may sometimes be desirable, or even necessary, to compare the hardness of the round with what the hardness would be if the material were flat.

Studies have been made to determine the correction due to the radius of curvature of a specimen. These studies have in some cases been carried out from a mathematical consideration of the problem and in others by actual tests made on carefully prepared specimens. Where corrections determined in either manner are used, the fact should be noted in the hardness specification, as all the corrections are only approximate, and it is necessary that in all cases the same correction factor be applied if the results are to be compared or duplicated at a later date.

A word of caution should be injected here. Even though the mathematical, empirical or experimental corrections are made, there is no assurance that a round specimen should have the same hardness as a flat specimen of the same composition and subject to the same treatment; or that a small round has the same hardness as a round of a larger diameter, when it is of the same composition and subjected to the same treatment.

Such factors as mass, depth of surface conditions, such as decarburization or superficially hardened surfaces, skin effect caused by die pressure, etc., may cause a change in hardness which would not be corrected by any factor based on the studies of radius of curvature alone. The type of support must also be considered and it must be ascertained that there is no error introduced into the test by the supporting anvil.

The four most commonly used testers, the Brinell, Vickers, Scleroscope and Rockwell, have been studied so far as the curvature effect is concerned, and each will be discussed separately. As this phenomenon is more pronounced with small diameter parts ½ in. or under, and as most of such testing is done with the Rockwell tester, the greatest portion of the discussion will be devoted to the Rockwell test.

Brinell

The National Bureau of Standards has made a very thorough study of the effect of curvature of surface as it affects the Brinell number. The conclusions as stated in Research Paper 903 are as follows: "The error in Brinell number due to curvature of the specimen may be reduced, in general, to less than 1 per cent by using the average of the two principal diameters of the indentation as the equivalent diameter, provided the minimum radius of curvature of the specimen is equal to or greater than 5 times the radius of the indenting ball."

This would require the radius of curvature of the specimen to be greater than 25 mm (1.0 in.) for a 10-mm ball, if the error is to be less than 1 per cent and the average of the two principal diameters used in the determination.

Scleroscope

It would be very difficult to determine the effect of radius of curvature on Scleroscope readings. It has been pointed out that the Scleroscope number is based on the fall and rebound of the drop hammer and also on the permanent indentation made by the hammer.

Furthermore, it is known that as the mass of the piece being tested decreases there is a falling off in rebound. Small diameter rounds thus are affected by lack of mass. This may be compensated by borrowing inertia from a proper support of sufficient mass, but the permanent indentation would still be affected by the radius of curvature. Since the type of support, mass, and radius of curvature all enter the picture, the best that can be said is that for rounds less than about 1¼ in. in diameter, the readings will be in error by a falling off in rebound. The amount of this error will be reduced by using a support which will increase the rebound.

Cylindrical pieces should be tested in a V block, and balls in a circular V block. Small rounds should be clamped in a grooved steel block (about 1½ in. wide) in a bench vise and the Scleroscope mounted on its swing arm.

Tubular or recessed parts require even more thought insofar as support is concerned. It may be necessary so to support the piece that vibratory effects are also eliminated. Often this is not possible, and an allowance must be made in the hardness specifications.

In order to obtain agreement on small rounds, it is necessary that the method of holding, mounting or clamping the sample be specified.

Differences may occur between the Model C and Model D Scleroscope on such parts, and here again allowance may have to be made in the hardness specification, as pieces of the same mass have different vibrations because the mass of the drop hammer is different in the two machines.

Rockwell Tester

W. E. Ingerson[1] developed a theoretical method for compensating the Rockwell hardness number on cylindrical specimens, due to differences caused by radius of curvature, when using the ⅟₁₆-in. diameter ball penetrator. The theory was applicable to either the normal or superficial model of the Rockwell tester. Values were calculated for specimen diameters from ⅛ to 1 inch. These results were then checked on specimens by Ingerson, and others working independently, and found to agree to very close limits.

In the theoretical work, it was assumed that materials had the same indentation hardness, if the same load and penetrator were used; the load supported per unit area is the same when equilibrium is reached. The area of contact perpendicular to the line of load application between a cylinder and sphere of ⅟₁₆-in. diameter was calculated for different depths of penetration, and this represented the normal area of contact. This area was equated to a circular area, which normally results when testing flat material, and the equivalent depth of penetration required to produce the same normal area of contact was calculated. From this the value of the equivalent Rockwell number was determined. In this work, the deformation of the penetrator was neglected. The complete theory is given below through the courtesy of the American Society for Testing Materials.

Theoretical Development

In developing the theoretical correction, one fundamental assumption was made. This was that materials may be said to have the same indentation hardness when, using the same penetrator and the same load, the load supported per unit area perpendicular to the line of load application is the same when equilibrium is reached. This is in accordance with Meyer's definition of hardness, and seemed more fundamental than Brinell's rather artificial use of spherical area of contact.

The plan of attack in developing the correction factor is to calculate the area of contact perpendicular to the line of load application, between a cylinder and a sphere, where the cylinder deforms and the sphere does not. This area we may call the normal area of contact. The normal area is calculated for various depths of penetration and cylinder radii. These areas are then equated to circular areas, and the equivalent penetration required to produce the same normal area of contact between a rigid sphere and a deformable flat surface is calculated. The assumed penetration into the cylinder and the equivalent penetration into a flat specimen are then converted into Rockwell numbers by the relation

$$R_n = 130 - 500P \quad \ldots\ldots (1)$$

where R_n = the Rockwell hardness number using the red figures, and
P = the penetration in millimeters.

The difference between these two values of R_n becomes a correction to be applied to the results of tests on cylindrical specimens to obtain the true hardness.

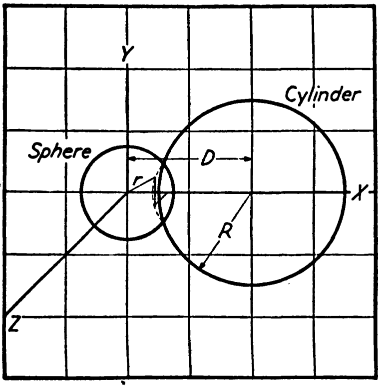


Figure 86. Coordinate system for determining contour of intersection of cylinder and sphere.

The coordinate system for calculating the area of contact is shown in Fig. 86. The origin of the Cartesian system is taken at the center of the sphere.

Let r = sphere radius,
R = cylinder radius,
P = penetration of sphere into cylinder, and
D = distance between centers = $R + r - P$.

If the cylinder is displaced along the X axis, and its axis is coincident with the Z direction, the equation of the cylinder is

$$Y^2 + (X-D)^2 = R^2 \quad \ldots\ldots (2)$$

The equation of the sphere is

$$X^2 + Y^2 + Z^2 = r^2 \quad \ldots\ldots (3)$$

If we eliminate X between Eqs. 2 and 3, the result will be the equation of the projection of the periphery of the contact area on the Y-Z plane, which is the above defined normal area. Rewriting Eq. 2, we have

$$(X-D)^2 = R^2 - Y^2 \qquad (2a)$$

or

$$(X-D) = \pm\sqrt{R^2 - Y^2} \qquad (2b)$$

then

$$X = \pm\sqrt{R^2 - Y^2} + D \qquad (4)$$

and

$$X^2 = R^2 - Y^2 \pm 2D\sqrt{R^2 - Y^2} + D^2 \qquad (5)$$

Substituting in Eq. 3

$$R^2 - Y^2 \pm 2D\sqrt{R^2 - Y^2} + D^2 + Y^2 + Z^2 = r^2 \qquad (6)$$

or

$$Z^2 = r^2 - R^2 - D^2 \pm 2D\sqrt{R^2 - Y^2} \qquad (7)$$

The + sign applies, since the negative value leads to imaginary roots.

While Eq. 7 is not readily recognizable as any familiar contour, when plotted it so closely resembles an ellipse for all values of the parameters in which we shall be interested, that it may be so considered for subsequent calculations. Figure 87 is a comparison of a representative curve plotted from Eq. 7 and an ellipse with the same major and minor axes. It is apparent that in considering these areas equal, little error is involved. The maximum error involved in this approximation is 0.6 per cent in area, representing 0.7 Rockwell number. This maximum occurs in the case of the smallest specimen and deepest penetration, where for other reasons the correction factor cannot be applied with confidence. The error varies roughly directly as the depth of penetration and inversely as the square of the specimen diameter.

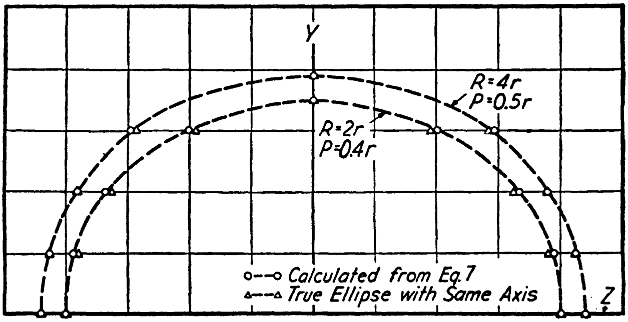


Figure 87. Comparison of projection of intersection of sphere and cylinder with ellipse.

Assuming the normal area to be elliptical, it is necessary to determine the major and minor axes for each value of P, compute the area (πab), equate it to a circular area, and solve for P', the penetration into a plane surface necessary to produce the same normal contact area.

The major and minor axes a and b may be determined by solving Eq. 7 for the conditions $y = 0$ and $z = 0$, respectively.

When $y = 0$, Eq. 7 becomes

$$\begin{aligned} Z^2 &= r^2 - R^2 - D^2 + 2DR \qquad (8)\\ &= r^2 - (R - D)^2 \end{aligned}$$

Now since

$$D = R + r - P \qquad (9)$$

$$R - D = P - r \qquad (10)$$

then

$$Z^2 = r^2 - (P^2 - 2Pr + r^2) = 2Pr - P^2 \qquad (11)$$

so

$$a = \pm\sqrt{2Pr - P^2} \qquad (12)$$

To determine the minor axis, set $z = 0$ in Eq. 7

$$2D\sqrt{R^2 - Y^2} = D^2 + R^2 - r^2 \qquad (13)$$

let

$$D^2 + R^2 - r^2 = M^2$$

then

$$4D^2(R^2 - Y^2) = M^4 \qquad (14)$$

or

$$y = \pm\sqrt{R^2 - \frac{M^4}{4D^2}} \qquad (15)$$

Now

$$M^4 = D^4 + 2D^2(R^2 - r^2) + (R^2 - r^2)^2$$

$$b = \pm\sqrt{\frac{R^2 + r^2}{2} - \frac{D^2}{4}\left(1 + \frac{(R^2 - r^2)^2}{D^4}\right)} \qquad (16)$$

For a particular size sphere and cylinder, we may by use of Eqs. 12 and 16, calculate the major and minor axes of the normal contact ellipse for various depths of penetration.

This area is

$$A_N = \pi ab \qquad (17)$$

Now if the sphere had penetrated a plane surface until the load was supported by the same normal area, this area would be

Table 6—Theoretical Rockwell Hardness Correction

All loads 1/16-in. penetrator—1/8-in. specimen—red figures

R_n	P	a	b	c^2	P'	R'_n
130	0	0	0	0	0	130.0
120	0.02	0.17706	0.14501	0.025675	0.01634	121.8
110	0.04	0.24880	0.20445	0.050867	0.03272	113.6
100	0.06	0.30274	0.24960	0.075563	0.04912	105.4
90	0.08	0.34727	0.28724	0.099751	0.06554	97.2
80	0.10	0.38568	0.32007	0.12344	0.08199	89.0
70	0.12	0.41964	0.34945	0.14664	0.09848	80.8
60	0.14	0.45016	0.3762	0.1693	0.1150	72.5
50	0.16	0.47791	0.4008	0.1915	0.1315	64.2
40	0.18	0.50334	0.4236	0.2132	0.1481	56.0
30	0.20	0.52678	0.4449	0.2344	0.1647	47.7
20	0.22	0.54850	0.4649	0.2550	0.1813	39.4
10	0.24	0.56868	0.4838	0.2751	0.1980	31.0
0	0.26	0.58750	0.5017	0.2947	0.2146	22.7

$$A'_N = A_N = \pi c^2 \qquad (18)$$

so

$$\pi ab = \pi c^2 \quad \text{or} \quad c = \sqrt{ab} \qquad (19)$$

Where c is the radius of the equivalent circle. If the sphere were penetrating a plane surface, P', the equivalent penetration can be expressed as

$$P' = r - \sqrt{r^2 - c^2} \qquad (20)$$

By Eq. 1, the equivalent, or corrected Rockwell number, R'_n is

$$R'_n = 130 - 500P' \qquad (21)$$

Table 6 presents the results of the above outlined calculation worked out in detail for the case where a 1/16-in. ball penetrator is used to make tests on a 1/8-in. rod.

Table 7 summarizes the results of the same calculation for the 1/16-in. ball penetrator used on 3/16, 1/4, 3/8, 1/2, 3/4 and 1-in. rods. Here some of the intermediate steps in the calculation are omitted, but the essential figures are presented.

Table 7—Theoretical Rockwell Hardness Correction for Measurements Made on Cylindrical Specimens

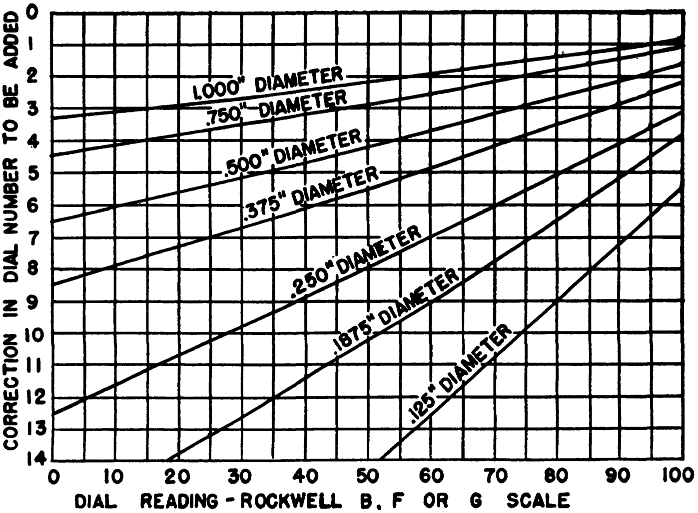
All loads—1/16-in. penetrator—red figures

		3/16-in. Specimen		1/4-in. Specimen		3/8-in. Specimen	
R_n	P	P'	R'_n	P'	R'_n	P'	R'_n
130	0	0	130.0	0	130.0	0	130.0
120	0.02	0.01734	121.3	0.01790	121.0	0.01853	120.7
110	0.04	0.03471	112.6	0.03584	112.1	0.03709	111.5
100	0.06	0.05211	103.9	0.05380	103.1	0.05567	102.2
90	0.08	0.06955	95.2	0.07181	94.1	0.07428	92.9
80	0.10	0.08701	86.5	0.08984	85.1	0.09291	83.5
70	0.12	0.10452	77.7	0.10790	76.0	0.11158	74.2
60	0.14	0.12206	69.0	0.12600	67.0	0.13027	64.9
50	0.16	0.13964	60.2	0.14413	57.9	0.14899	55.5
40	0.18	0.15724	51.4	0.16230	48.8	0.16774	46.1
30	0.20	0.17489	42.6	0.18050	39.8	0.18652	36.7
20	0.22	0.19257	33.7	0.19873	30.6	0.20532	27.3
10	0.24	0.21029	24.9	0.21700	21.5	0.22415	17.9
0	0.26	0.22804	16.0	0.23531	12.4	0.24302	8.5

		1/2-in. Specimen		3/4-in. Specimen		1-in. Specimen	
R_n	P	P'	R'_n	P'	R'_n	P'	R'_n
130	0	0	130.0	0	130.0	0	130.0
120	0.02	0.01887	120.6	0.01922	120.4	0.01941	120.3
110	0.04	0.03776	111.1	0.03846	110.8	0.03883	110.6
100	0.06	0.05667	101.7	0.05772	101.1	0.05827	100.9
90	0.08	0.07561	92.2	0.07699	91.5	0.07772	91.1
80	0.10	0.09456	82.7	0.09629	81.8	0.09718	81.4
70	0.12	0.11354	73.2	0.11559	72.2	0.11666	71.7
60	0.14	0.13255	63.7	0.13492	62.5	0.13615	61.9
50	0.16	0.15157	54.2	0.15427	52.9	0.15565	52.2
40	0.18	0.17062	44.7	0.17362	43.2	0.17517	42.4
30	0.20	0.18970	35.2	0.19300	33.5	0.19470	32.6
20	0.22	0.20880	25.6	0.21239	23.8	0.21424	22.9
10	0.24	0.22792	16.0	0.23180	14.1	0.23380	13.1
0	0.26	0.24706	6.5	0.25123	4.4	0.25337	3.2

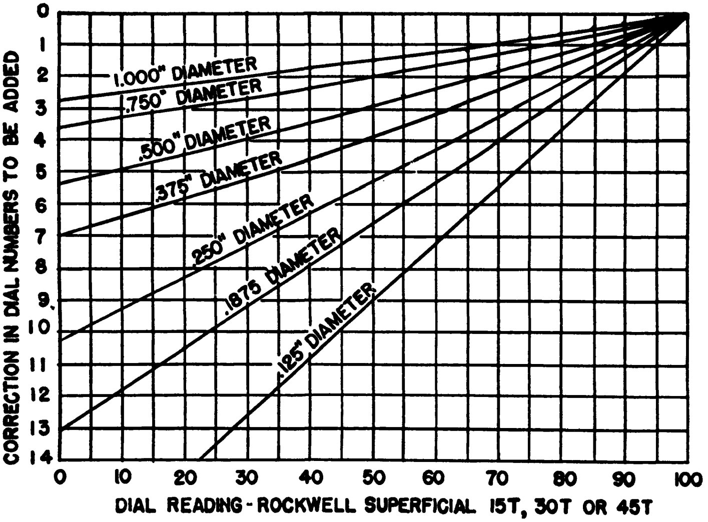
As such matters as "piling-up" and "sinking-in" of material around the impression, as well as the fact that the recovered impressions are not truly spherical, were neglected, the theory was checked against a series of carefully prepared specimens which were tested on the cylindrical surfaces and the flat ends, and it was found that the theoretical and experimental results agreed, in general, to better than one point.

Experimental tests made in the Standardizing Laboratory of the Wilson Mechanical Instrument Co. on a large number of round speci-



(*From W. E. Ingerson's work*)

Figure 88. Hardness correction factors for cylindrical specimens. Rockwell B, F, or G scale.

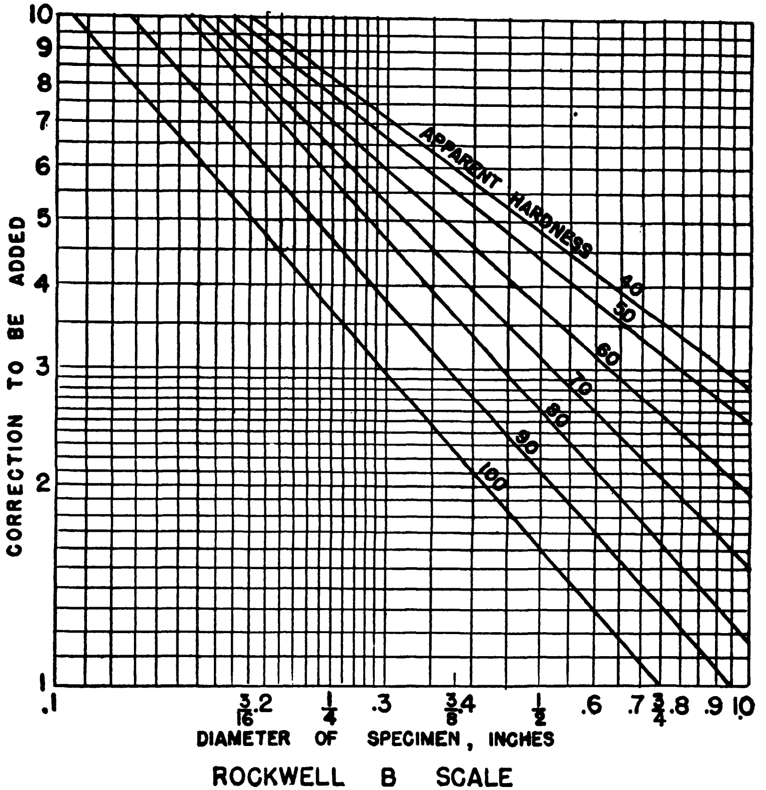


(*From W. E. Ingerson's work*)

Figure 89. Hardness correction factors for cylindrical specimens. Rockwell 15T, 30T, or 45T scales.

mens likewise supported the theory developed by Ingerson to better than 1 Rockwell number.

Figs. 88 and 89 show the corrections to be added to readings obtained on the "B," "F" and "G" scales of the normal Rockwell tester and the 15T, 30T and 45T scales of the Rockwell superficial hardness tester to obtain so-called true Rockwell numbers. The data for these curves are taken from Ingerson's work.



(From David Wallace's work)

Figure 90. Hardness correction factors for cylindrical specimens. Rockwell B scale

David Wallace of the Sperry Gyroscope Co.[2] completed a very thorough investigation of the same problem following in general Ingerson's procedure, and the results of his tests on the B and 30T scales are shown in Figs. 90 and 91. It will be observed that there is very close agreement in the results.

A theoretical determination of errors when using the diamond Brale penetrator on the Rockwell or Rockwell superficial tester is more involved, because the shape of the Brale penetrator is a cone with a 2-mm radius sphere for an apex. Applying the theory developed by Ingerson to tests made with the Brale penetrator for both the normal and superficial models of the Rockwell testers, but making more assumptions due to the complications of the shape of the diamond Brale penetrator, a series of curves may be obtained as shown in Fig. 92 for the C scale and Fig. 93 for the 30N scale. Wallace also investigated these scales and his results are shown in Figs. 94 and 95. There is good agreement between his results and those derived as described above and shown in the curves.

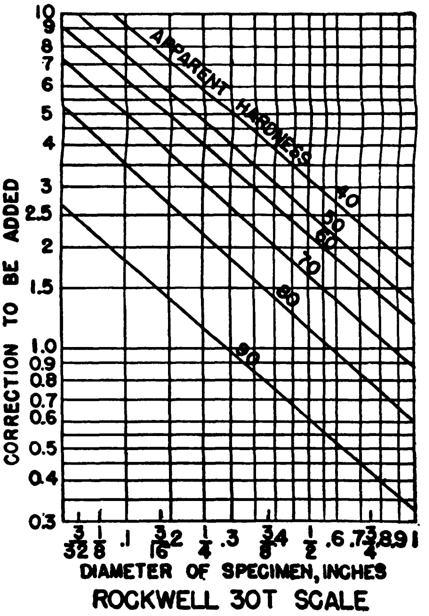


Figure 91. Hardness correction factors for cylindrical specimens. Rockwell 30T scale.

(*From David Wallace's work*)

W. L. Fleishman and R. S. Jenkins[3] of the General Electric Co., Fort Wayne Works, and G. E. Poole and J. Hunt of Pratt & Whitney Aircraft[4] have likewise completed work along this subject.

While there is not too close agreement between these different investigations, there is, nevertheless, agreement within practical limits, and as no mathematical proof is available without resorting to the expediency of making several assumptions, and as actual tests are influenced by many practical considerations, the curves shown give good average corrections.

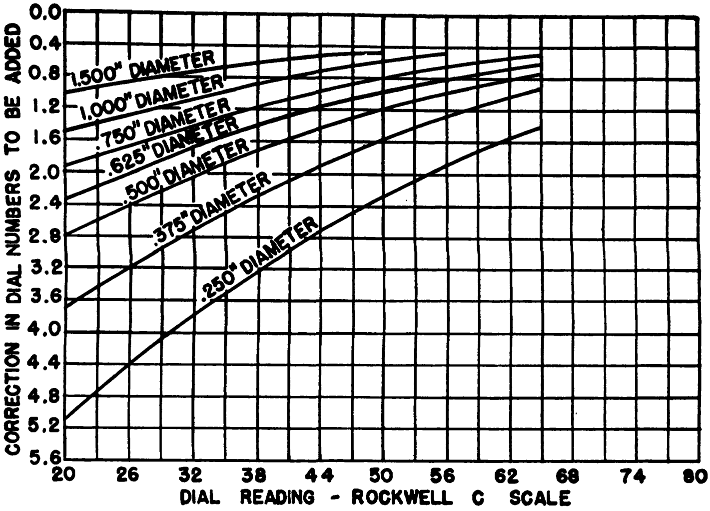


Figure 92. Hardness correction factors for cylindrical surfaces. Rockwell C scale.

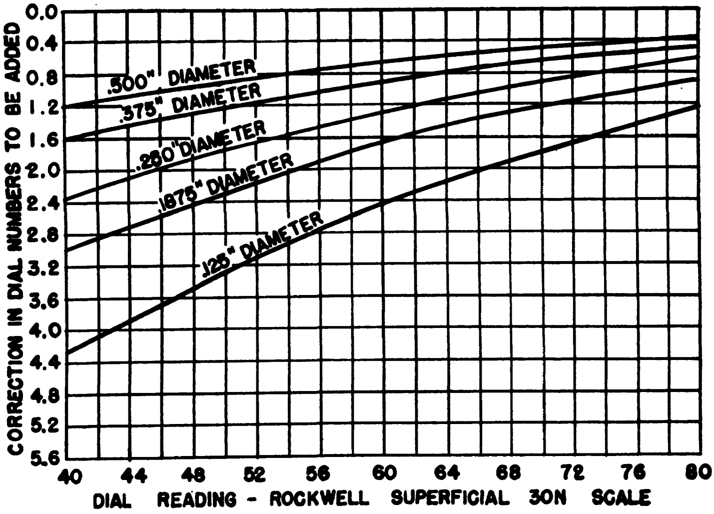
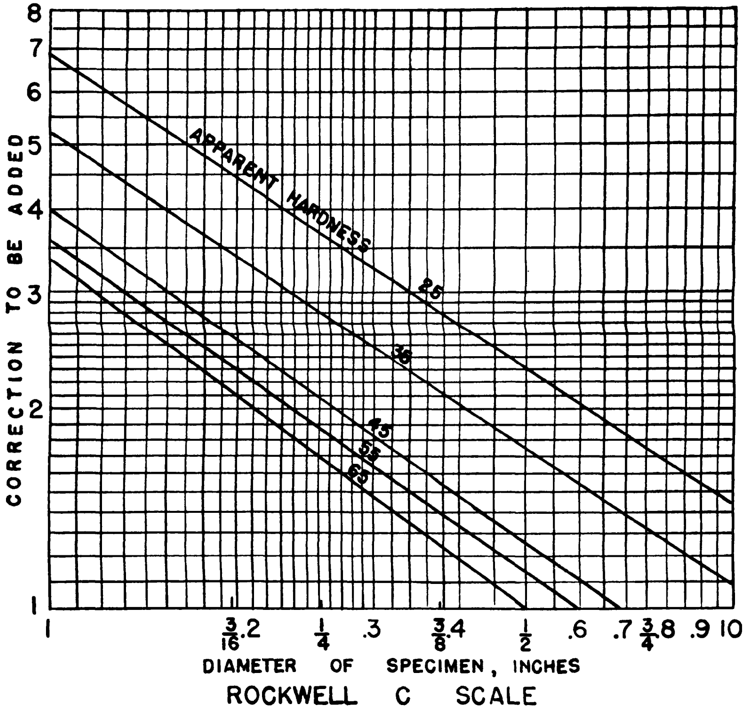


Figure 93. Hardness correction factors for cylindrical surfaces. Rockwell 30N scale.



(From David Wallace's work)

Figure 94. Hardness correction factors for cylindrical surfaces. Rockwell C scale.

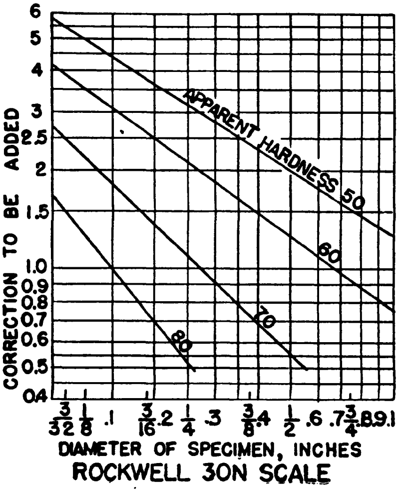


Figure 95. Hardness correction factors for cylindrical surfaces. Rockwell 30N scale.

(From David Wallace's work)

136° Diamond Pyramid Test

Very little work has been published with reference to 136° diamond pyramid tests on cylindrical surfaces. The general case, of testing cylinders with the corners of the indenter making an angle with the cylinder, presents a very complicated mathematical problem. It may be considerably simplified by making two sides of the impression parallel to the axis of the cylinder. Under such a condition the formula * for the slant area of the diamond pyramid impression on a cylinder may be approximated as follows:

$$\text{Total area in sq mm} = 5.393d^2 + .3146\frac{d^3}{D}$$

where d = diagonal of impression in mm
D = diameter of cylinder in mm

Using this formula DPH values may be completed for different loads for various diameter of cylinders by dividing the applied load in kilograms by the area as determined above.

The shape of the 136° diamond pyramid indenter is advantageous in that it may be oriented so that the one diagonal may be brought parallel to the axis of the cylinder. In this manner the difference between diagonals indicates whether or not a reliable hardness value is being obtained. Any appreciable difference between diagonals as, for example, greater than 10 per cent, would introduce considerable error if the standard tables were used.

References

1. Ingerson, W. E., "Rockwell Hardness of Cylindrical Specimens," *Proc. Am. Soc. Testing Materials,* 39 (1939).
2. Wallace, D., "Rockwell Hardness Correction Factors," *Materials and Methods* (February, 1946).
3. Fleischman, W. L., and Jenkins, R. S., "Rockwell Hardness (Diamond Penetrator) of Cylindrical Specimens," *Metal Progress* (February, 1945).
4. Poole, G. E., and Hunt, J., "Rockwell Hardness Corrections for Rounds," *Metal Progress* (May, 1947).

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* Formula obtained from personal correspondence with British Standards Institution.

Chapter XIV

Hot Hardness Testing

The determination of the physical properties of metals at elevated temperatures is very difficult, and hardness tests at elevated temperatures have been studied as a relatively simple means of determining strength. Such investigations have been made for some time, but the development of high-powered machines, such as the turbo-jet and rocket, has increased the value of and need for the data obtained from such testing. Metals now must withstand higher temperatures and pressures and the metallurgist no longer can afford to guess. Alloys have been developed to withstand high stresses and temperatures up to 1500° F.

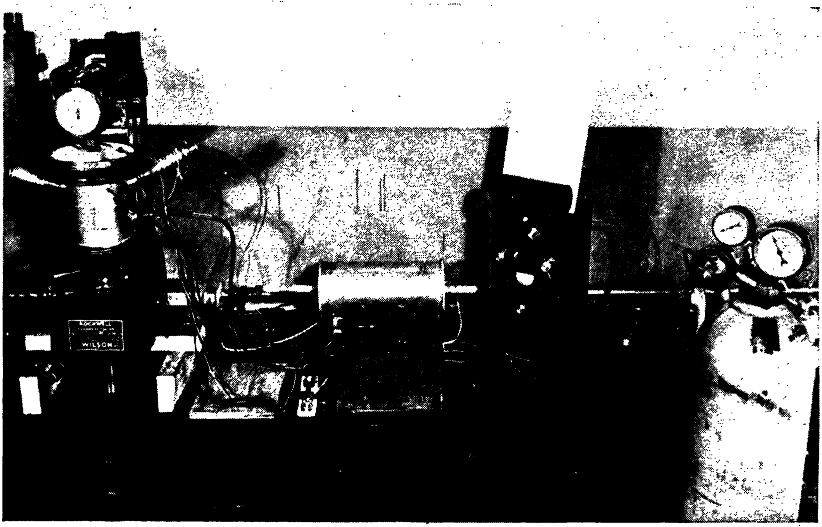
Tests at elevated temperatures will also enable the research engineer to follow the course of structural phenomena as metals change from high temperature to room temperature.

While tests can be made on the Brinell, Vickers or Rockwell hardness testers, most work is done on the Vickers or the Rockwell. Usually a small impression is desired so that many readings can be taken on a single sample. Furthermore, most tests are made on hardened and tempered specimens when the use of the Brinell test is limited.

Rockwell Hardness Tester

The use of the Rockwell tester permits measuring the hardness of the sample without cooling the sample for measuring the impression. Usually the specimen is heated in a specially designed furnace mounted on a testing table attached to the elevating screw of the tester. The penetrator is heated in the furnace along with the specimen and the tests made in the usual manner.

Details of an elaborately designed method for determining Rockwell hardness numbers at elevated temperatures have been described by Dr. Morris Cohen of the Massachusetts Institute of Technology. The method requires little explanation, but it should be stated that the oil seal, several joints and parts of the tester above the furnace are water-cooled. The indenter holder is equipped with heating coils to insure proper temperature control of the indenter. Lateral movement of the specimen is allowed by permanently attaching the flanged furnace



(*From Dr. Morris Cohen's work*)

Figure 96. Complete apparatus for hot hardness testing.

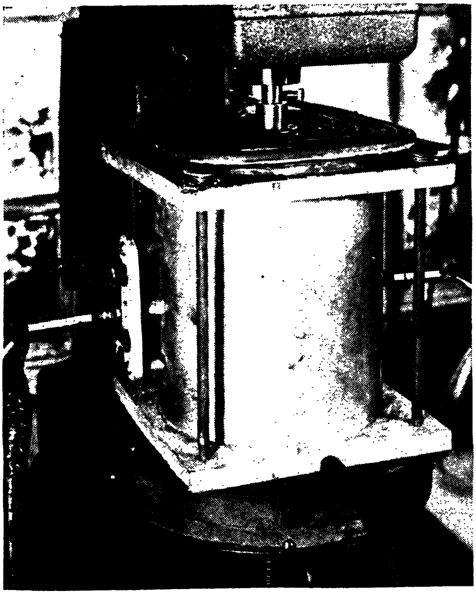


Figure 97. Furnace for heating specimen for hot hardness testing.

(*Courtesy Universal-Cyclops Steel Corp., Bridgeville, Penn.*)

cover to the indenter extension and allowing the cover to dip into a trough of oil. This arrangement also permits applying the minor load. The complete setup is shown in Fig. 96.

A much simpler unit has been developed by the Universal-Cyclops Steel Corp., and was described recently.[1] The diamond Brale penetrator is held in a type 19–9DL stainless-steel plunger extension. The specimen rests on an anvil made from the same material. The furnace is placed on a testing table attached to the elevating screw. The temperature of the furnace and specimen is controlled by means of thermocouples. The furnace cover is water-cooled to protect the tester, and the lower part of the instrument is protected by a water-cooled jacket surrounding the testing table. Fig. 97 shows the furnace in position on the testing table.

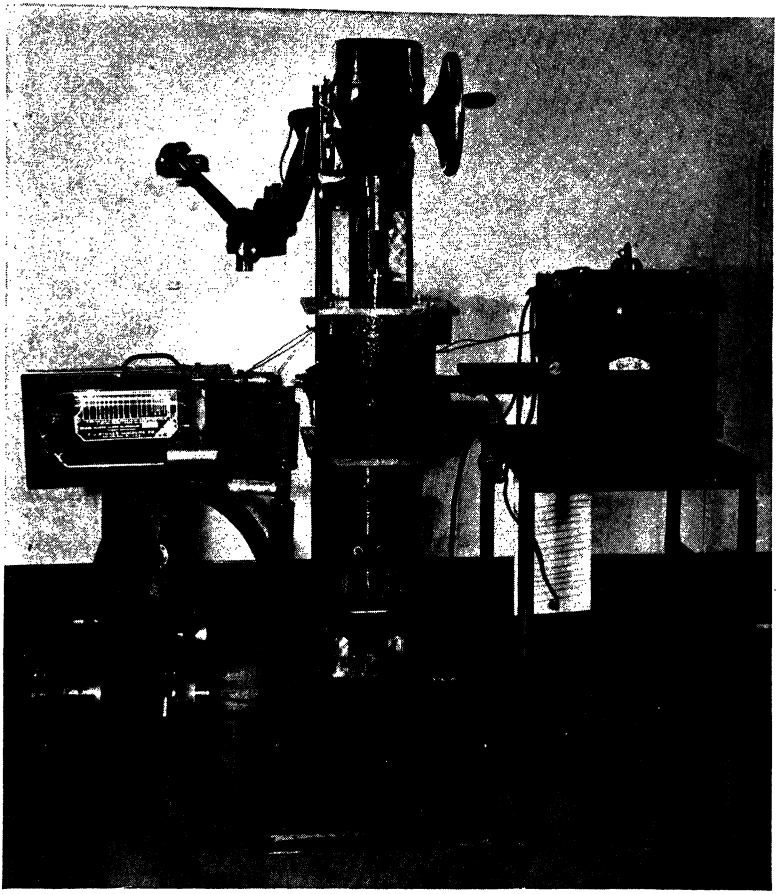
Special mountings are required for the diamond Brale penetrators used in hot hardness. These penetrators withstand temperatures satisfactorily up to 1500° F. under certain conditions depending on the type of atmosphere used in the furnace. It is possible that with dead air atmosphere the mounting would deteriorate in a relatively short time, whereas with pure nitrogen atmosphere very satisfactory results would be obtained with reference to the suitability of the mounting. The diamond itself will probably show no effect up to above 2000° F.

Vickers Tester

F. P. Bens[2] has described in detail the use of the Vickers machine for hardness testing of metals at elevated temperatures (Fig. 98). A vacuum furnace was provided which permitted heating the sample and indenter to the desired temperature and protecting them from oxidation. The vacuum was maintained by a small mechanical vacuum pump. A device was built into the furnace for moving the specimen under the indenter without destroying the vacuum.

The load is applied by means of a flexible piston suspension which enters the furnace through a piston made from "Invar" acting in a stainless steel cylinder. The diamond indenter is attached to the piston. By raising the stage of the tester the specimen is brought into contact with the specimen. The load is then applied and the testing cycle completed.

The 136° diamond pyramid number is calculated in the usual manner, except that the load applied must be corrected for the additional weights of the piston and suspension, the force on the piston caused by the air pressure, and the approximate frictional value between the piston and the cylinder. The error resulting from making the indentation at an elevated temperature and reading the diagonals at normal tem-



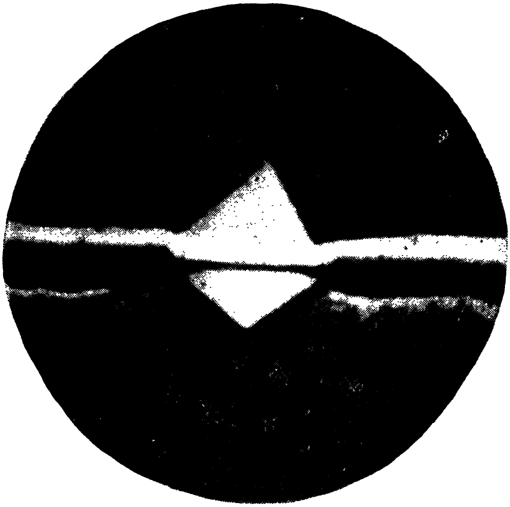
(*Courtesy F. P. Bens*)

Figure 98. Hot hardness testing with Vickers tester.

perature is so slight that it may be neglected. Satisfactory life of the indenter may be had for values up to 1700° F. in a vacuum heating chamber.

References

1. Zmeskal, O., "Hot Hardness Testing," *Metal Progress* (January, 1947).
2. Bens, F. B., "Hardness Testing of Metals and Alloys at Elevated Temperatures," *Trans. Am. Soc. Metals,* 38 (1947).



(Courtesy American Optical Co., Buffalo, N. Y.)

zirconium nitride crystal

tin oxide crystal

Figure 99. Microcharacter scratch test.

ness number is calculated. The rate of application of load, length of time for applying the load, and removal of the load are automatic. The load is applied for about 15 seconds. Light loads are applied in such a manner as to eliminate errors due to inertia. Dead weight loads of 25 to 3600 grams are available.

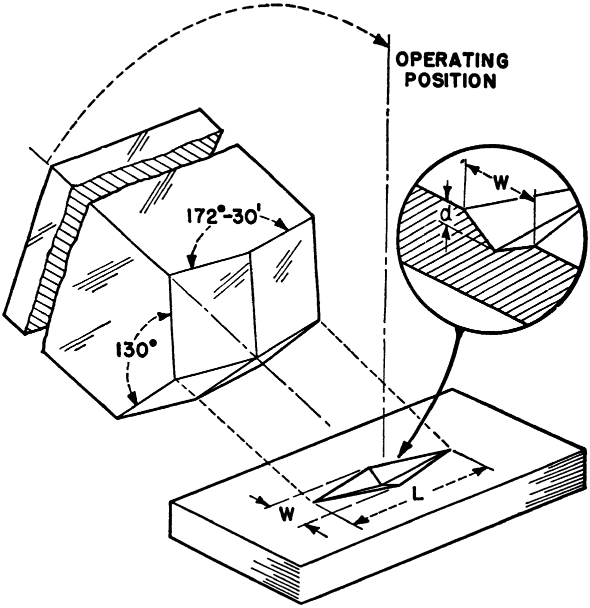


Figure 100. Knoop indenter.

For making indentations in selected small areas, an accurately designed mechanical stage, known as the Microton, is provided. An area of a few thousandths of a square millimeter can be accurately located under the microscope; the specimen is then moved under the indenter, the indentation made on the selected location, and the specimen returned under the microscope for the purpose of reading the dimensions of the impression.

The indentation number is taken as the ratio of the applied load to the unrecovered projected area, or by formula:

$$I = \frac{L}{A_p} = \frac{L}{l^2C_p}$$

I = Knoop hardness number
L = Load (in kg)
A_p = Unrecovered projected area of indentation (in sq mm)
l = Measured length of long diagonal (in mm)
C_p = Constant relating l to the projected area

The length of the long diagonal is the only measurement required; the number is calculated from this length, since it is but little affected by elastic recovery when the load is removed. In actual practice, the Knoop number is obtained from a table in order to eliminate calculations (see Appendix).

A metallurgical microscope with filar micrometer eyepiece is mounted on the instrument. For most work, a 4-mm dry objective lens is used which, in combination with the Bausch & Lomb Filar Micrometer, provides a magnification of about 650 diameters. Indentation lengths of from about 20 microns to 1000 microns will be encountered. The measuring microscope, therefore, must be capable of an accuracy of at least 1 micron.

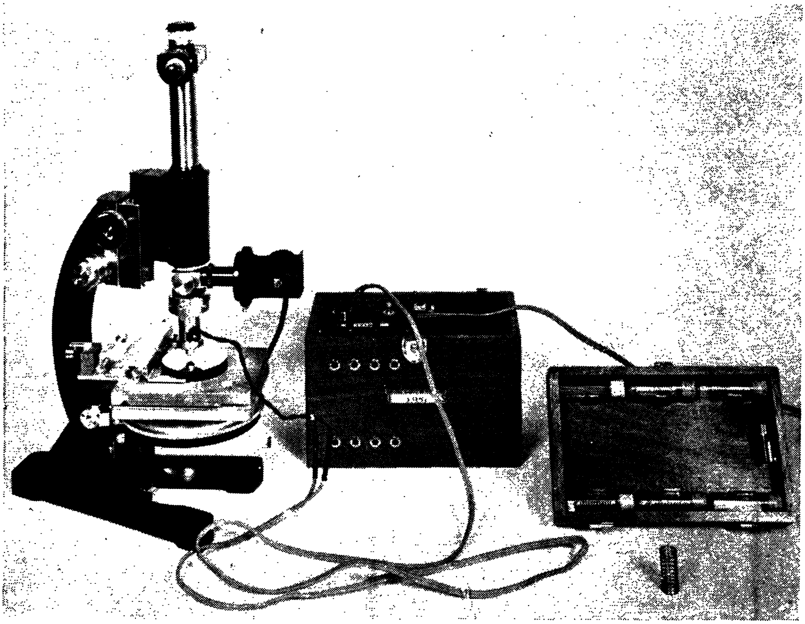


Figure 101. Eberbach microhardness tester.

The Tukon tester is readily adapted for use with the 136° diamond pyramid indenter, if the use of such an indenter offers an advantage.

Another type of microhardness tester is the Eberbach, manufactured by Eberbach & Son Company, Ann Arbor, Michigan. It is shown in Fig. 101 and consists of a spring-loaded 136° diamond pyramid indenter moving axially in a bearing which may be attached to the tube of a microscope in place of the objective lens mount. In making the test, the indenter is lowered into the specimen by means of the fine adjustment in the microscope. An electronic device indicates when the full indenting load is applied to the specimen.

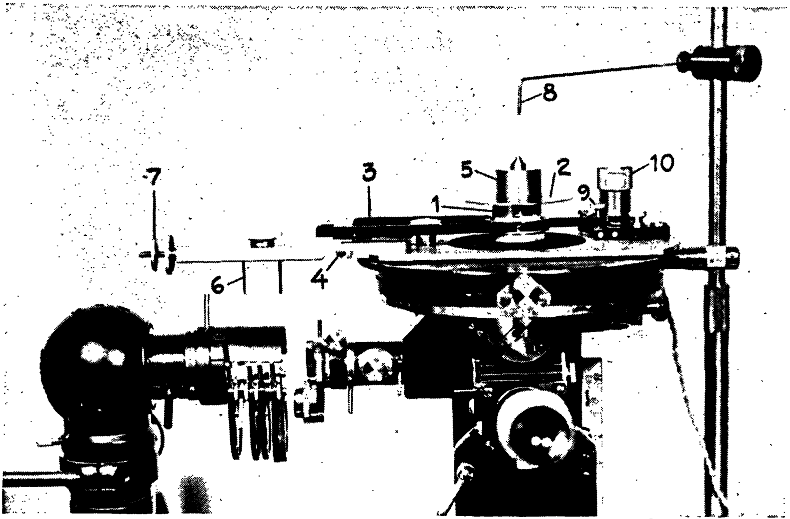
With the vertical type microscope, loads of from about 25 to 800 grams are available; with a microscope in which the specimen is viewed from below, a range of from about 7 to 800 grams is provided, the difference being due chiefly to the weight of the indenter spindle and springs. The load is changed by removing one spring and inserting another; the instrument should be calibrated each time a spring is changed.

A variety of microhardness testers is in use in European countries. Each applies the load and locates the specimen in a different manner. Results obtained on one instrument are generally not comparable to those obtained on other instruments because of errors involved in the manner and rate of applying the load. Often the loads are applied by spring pressure.

One of the best known of these instruments is the Bergsman's microhardness tester.[2] This is generally mounted on a metallographic microscope, usually of the inverted type, and is illustrated in Fig. 102. The numbers in the photograph refer to the following: (1) specimen holder, (2) weight disk, (3) lever, (4) axle, (5) indentation load—fixed interchangeable weight—which is placed on the weight disk after counterbalancing by the adjustable counterweights (6) and (7), (8) indicating pointer for adjusting weight to correct position centered above the diamond point, (9) electric contact broken when diamond point lifts the specimen and its holder, (10) electric lamp showing when contact (9) is broken.

In operation the specimen is clamped in the holder with the polished surface to be tested facing downward. The weight disk is applied and the attachment counterbalanced. Then the indenting weight is added. The spot on the specimen which is to be tested is selected and the microscope objective is replaced by the indenter holder in which the diamond has already been centered. The test is made by lowering the specimen stage with the coarse adjusting screw and proceeding with the fine adjusting screw until the diamond almost touches the specimen. The load is applied by continuing to move the fine adjusting screw until the diamond point lifts the specimen and its holder. At this point an electric circuit is broken and a lamp is extinguished. Under such conditions the weight is applying the load and the diamond makes the impression. After a suitable length of time (usually 15 seconds) the specimen stage is raised and the diamond holder is replaced by the objective and the impression may be measured.

The 136° diamond pyramid indenter is used in this test. The impres-



(*Courtesy of Uddeholm Co. of America, Inc., New York, N. Y.*)

Figure 102. Bergsman's microhardness tester mounted on an inverted microscope.

1. Specimen holder; 2. weight disk; 3. lever; 4. axle; 5. indentation load — fixed interchangeable weight — which is placed on the weight disk after counterbalancing by the adjustable counterweights (6) and (7); 8. indicating pointer for adjusting weight to correct position centered above the diamond point; 9. electric contact broken when diamond point lifts the specimen and its holder; 10. electric lamp showing when contact (9) is broken.

sion diagonals are measured by means of an eyepiece screw micrometer and the 136° diamond pyramid number calculated in the usual manner. Loads of from 1 to 200 grams are available.

The attachment may be used as a scratch tester under loads of from 0.5 to 3.0 grams by displacing the object stage with the load applied.[3]

Applications

It would be impossible to discuss all applications of the microhardness test, as they are manifold. They may be classified, however, into a reasonable number of uses along similar lines, and typical examples of each group will be discussed. One such grouping is as follows:

1. Small precision parts
2. Surface layers
3. Thin materials and small wires
4. Exploration of small areas
5. Hardness of constituents
6. Tool steels, tips of cutting tools

Typical examples of small precision parts are encountered in the manufacture of timepieces, and the Hamilton Watch Co. considers hardness one of the most important physical properties of watch parts. Prior to the development of the Tukon tester none of the existing hardness-testing equipment was capable of making tests on such small parts. This company was one of the first to experiment with microhardness for research work and in a short time it was found it could be used for control work on critical parts and materials.

Watch parts and drill rod are mounted in thermosetting plastic and polished like metallographic specimens. Since the size of the indentation can be varied by changing the load, it is possible to test every type of watch part successfully, even the smallest. Frequent tests have been made, for example, on balance staff pivots, screws, pinions, studs, pins, click springs, etc. In a period of two months over 4600 tests were made for control purposes.

Fig. 103 at × 6 shows minute pinions mounted for test; at × 250 it shows Knoop indentations made with a load of 300 grams on one side of one tooth. Fig. 103a, again at × 6, shows pallet spindles mounted for test. The pivots are 0.010 in. long and 0.0049 in. in diameter. The picture at × 250 shows Knoop indentations made with load of 500 grams.

Similar testing of watch parts is carried out by Elgin National Watch Co. and the United States Time Corp., and precise knowledge and control of the hardness of many tiny parts are obtained. The use of the microhardness tester is both for research and production control.

Instrument pivots, surgical needles and the tiny pellets of pen points are among other small parts tested with the Knoop indenter.

The quantitative control of the hardness of shallow electroplated surfaces or other hard, thin surface coatings, and the probing of limits of decarburization have for many years offered a challenge to the hardness test; but by using the microhardness test such surfaces may be accurately tested. The Tukon tester and the Knoop indenter have been a great aid in measuring the hardness of different electroplates. Although not confined to chromium, considerable work has been done on the determination of the hardness of chromium plate.

It has been determined that the hardness of chromium plate depends for the most part on the rate of deposition of the chromium when all other factors, such as chemical composition of the plating solution and the temperature of the solution, remain constant.

Most chromium plate applied to increase wear resistance ranges between 800 and 1050 Knoop hardness numbers under a load of 100 grams. Decorative chromium plate is normally harder due to the increased plating rate for decorative work. Values as high as 1200 (100-

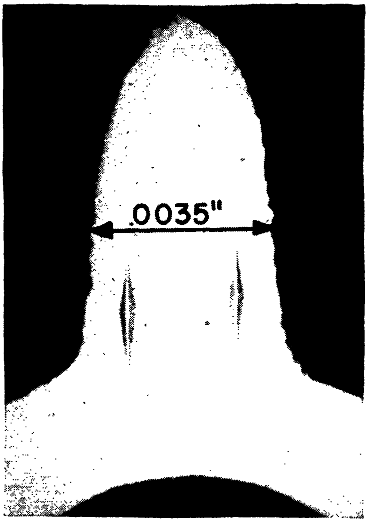
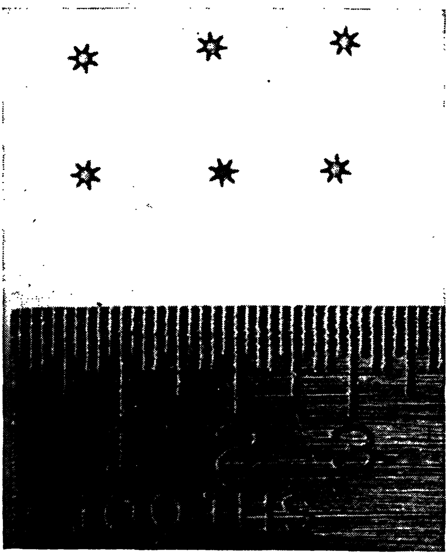


Figure 103. Minute pinions, 0.0288 inch in diameter. Load 300 grams. Knoop indentations. (250X *mag.*)



(6X *mag.*)

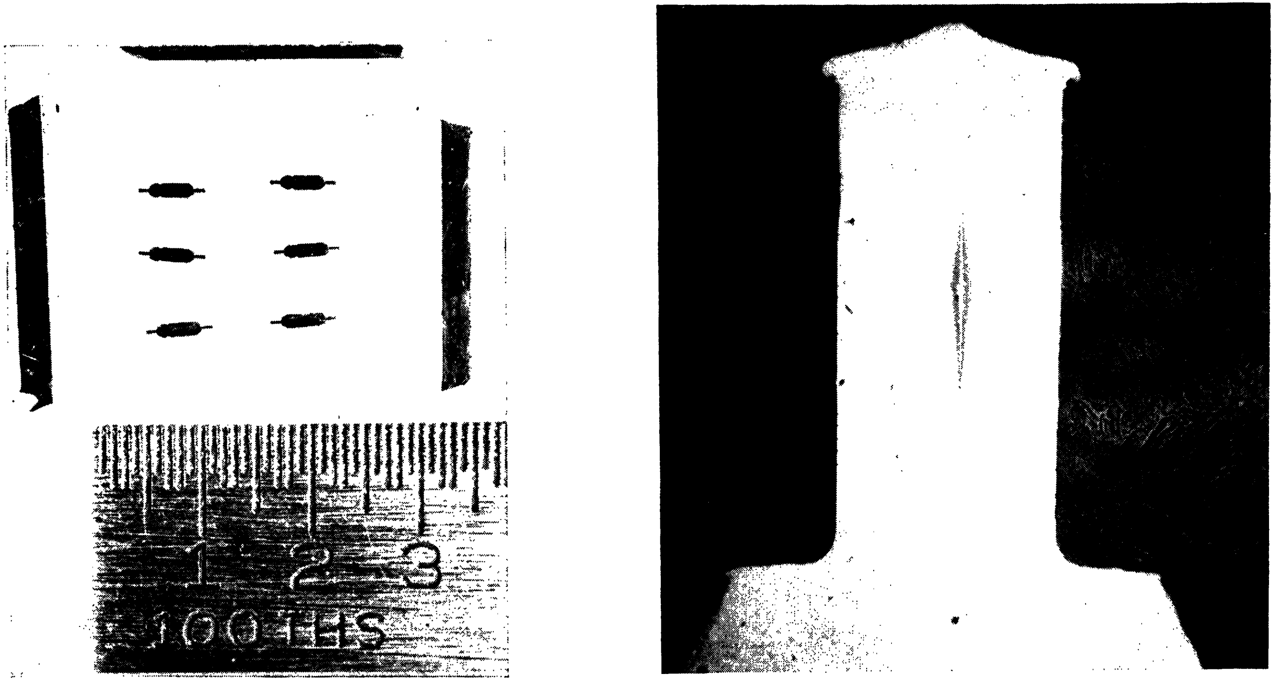


Figure 103a. *Left:* Pallet spindles, with pivots 0.010 inch long and 0.0049 inch in diameter (6X *mag.*). *Right:* Knoop indentation made with load of 500 grams on the spindle pivot (250X *mag.*).

gram load) have been obtained under certain conditions. One specification for the hardness of chromium plate on engine piston rings requires a Knoop Hardness value of at least 775 with a load of 100 grams.

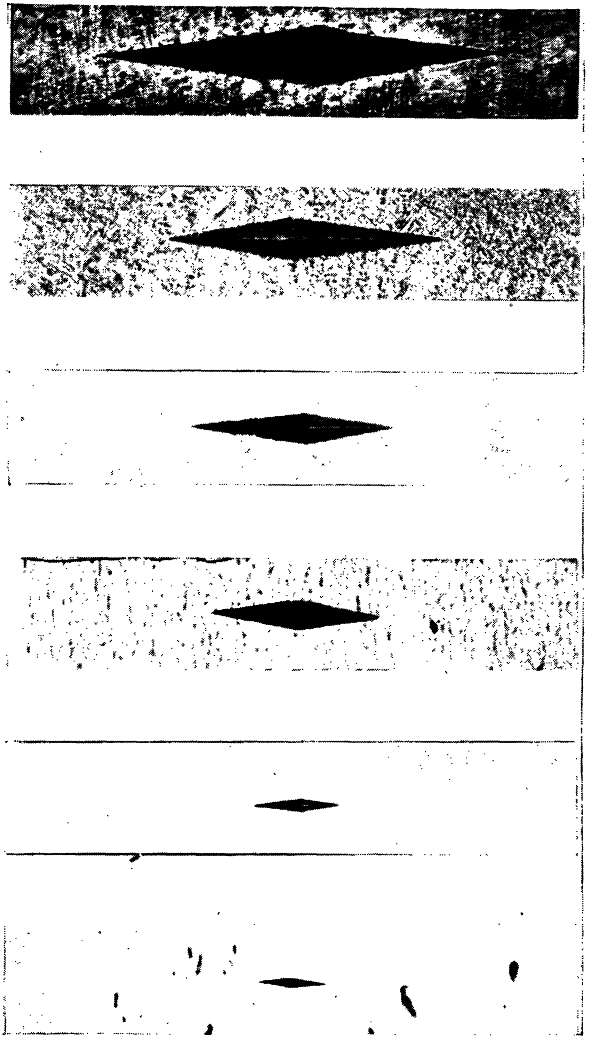
With reference to the effect of various base metals on the hardness of chromium plate, it is now established that the base metal has no effect on the hardness, provided that the plate is of reasonable thickness. Satisfactory measurements of hardness of plates 0.0005 in. thick have been made without any effect of the base metal being apparent.

The hardnesses of other plated surfaces have been tested on the Tukon tester; impressions made on electrodeposits of cadmium, silver, zinc, copper, nickel and chromium are shown in Fig. 104. These values should not be considered as representative of the plated surfaces under all conditions. Such factors as current density, temperature and composition of plating solution, variation in hardness from the outside to the inside of the plate and structure of the electrodeposited metal, all influence the hardness. Morrison and Gill[4] have evaluated the surface hardness of nitrided cases of nitrided high-speed steel where the microscopic case depth showed only 0.0005 in.

Knoop hardness gradients through carburized cases have given invaluable information to the metallurgist. Fig. 105, reproduced through the courtesy of Mr. R. H. Jacoby, is an ideal manner in which to present the data. Here is shown the gradient as well as a photomicrograph of the section on which the tests were made.

Common practice is to specify case depths of 0.015 to 0.020 in. and after heat treatment, to grind the surface. If 0.010 or 0.012 in. is removed there is a possibility of getting below the optimum hardness values. It is possible that even high magnification metallographic examination would fail to determine this, as it is difficult to distinguish between martensite and tempered martensite when there is a difference of only 3 or 4 Rockwell C scale numbers.

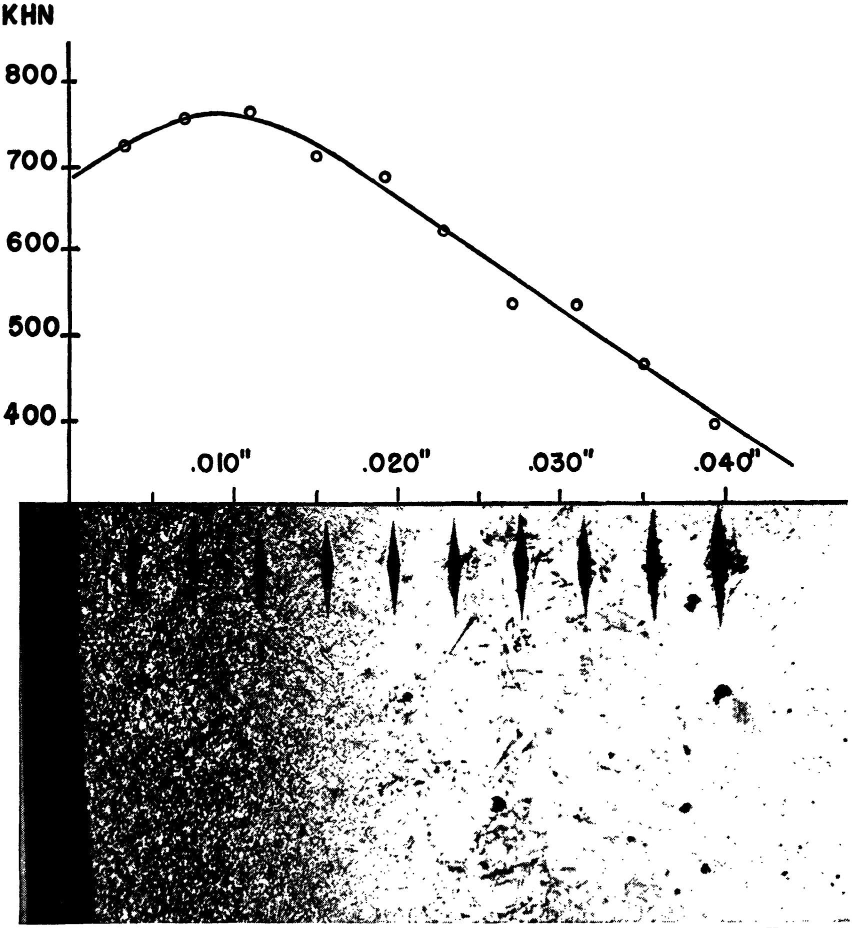
On extremely thin case-hardened materials, such as obtained by cyaniding, the information obtained with the Tukon Tester and Knoop Indenter is very valuable. Because of the shallow depth of case, it is important to know the effective case depth in cyaniding, and the Knoop hardness in the transition zone gives this information (Fig. 106). These samples are 0.051 in. thick A.I.S.I. C1010 cold-rolled steel, hardened in a standard sodium cyanide bath containing 15.5 per cent cyanide and allowed to remain at 1550° F for 10 minutes before being quenched. All specimens were file hard, and the load was 500 grams. Fig. 106a shows a cyanide case with depth of about 0.004 in. As many as 10 hardness readings on a section of a case have been obtained by staggering the impressions.



Metal	Knoop No.	Converted Rockwell Number
Cadmium	37	
Silver	60	
Zinc	119	63 B
Copper	163	82 B
Nickel	557	51 C
Chromium	935	65.5 C

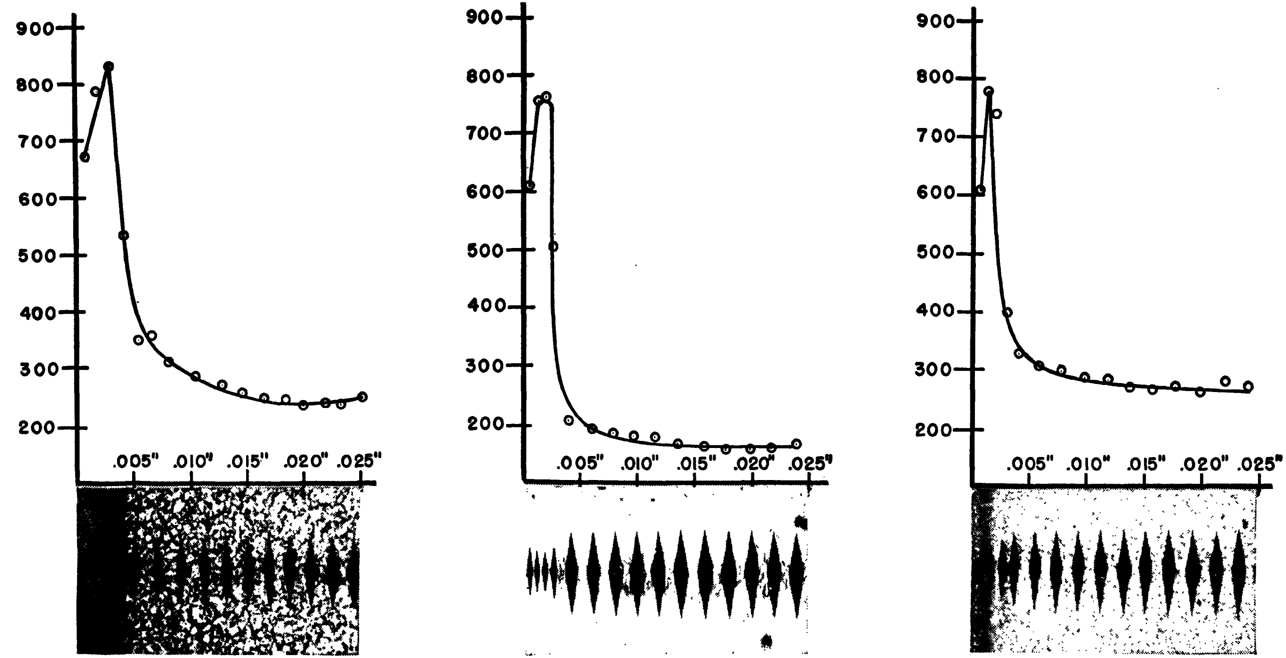
(*Courtesy General Electric Company, Bridgeport, Conn.*)

Figure 104. Hardness of electrodeposited metals. Tested on the Tukon microhardness tester. 100 gram load (250X *mag.*).



(*Courtesy Mr. R. H. Jacoby*)

Figure 105. Knoop hardness gradient through carburized case (1 kg load).

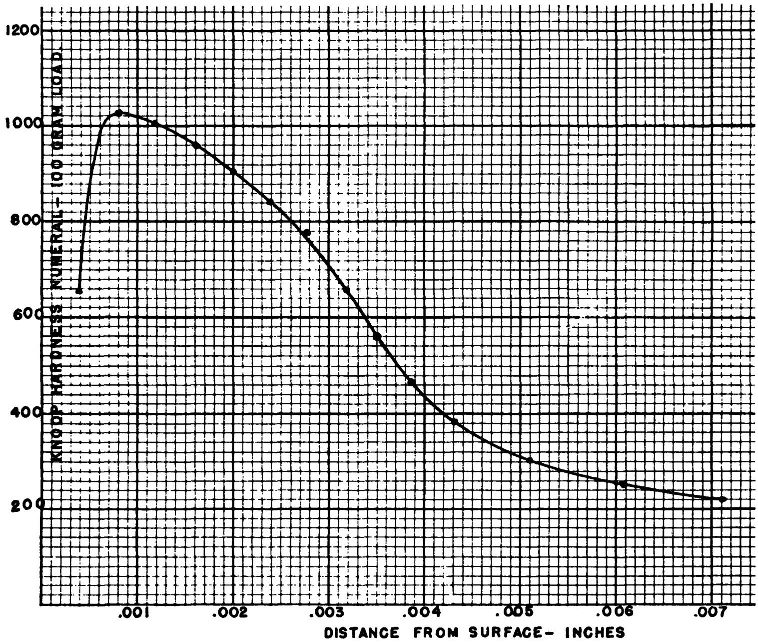


Quench:	10 % brine	Gulf Super	Houghton's Soluble No. 2
Temperature:	78° F.	140° F.	80° F.
Surface Hardness:	784 KNH	780 KNH	740 KNH
Case Depth:	.0035″	.003″	.0025″
Etch:	4 % nital	none	3 % nital
Draw:	none	none	none

Figure 106. Hardness gradient on thin case-hardened materials (65X *mag.*). Applied load 500 grams.

On induction-hardened parts, it is possible, with the Tukon tester, to obtain a survey of depth of hardening and to regulate the heating cycle accordingly. Here again probing of the transition zone with the micro-indentation has in some instances served better than the high-power metallographical microscope.

D. L. Martin of the General Electric Co.[5] has published work showing the Knoop hardness at 0.005 to 0.010-in. intervals across the transverse surface of induction-hardened specimens, together with a plot of the hardness penetration curve for each specimen. In this manner, comparison has been made of the hardening characteristics of numerous steels, and studies of the effect of temperature, composition, and prior microstructures on induction-hardening characteristics have been carried out.



(Courtesy General Research Laboratory, Underwood Corp., Hartford, Conn.)

Figure 106a. Knoop hardness gradient .004 inch cyanide case.

Fig. 107 (left) shows the Knoop hardnesses on induction-hardened steel parts. The indentations are 0.010 in. apart, and the load is 500 grams. The white surface layer is chromium. It is obvious that there is room for additional readings if desired. Fig. 107 (right) shows a decarburized layer resulting from austenizing in improperly deoxidized nitrogen. The indentations are 0.005 in. apart and the load 500 grams.

In studying the limits of decarburization, depths appearing on carburized surfaces that are less than 0.001 in. have been detected with the Knoop indenter when testing the surface. It is evident that the use of light loads with either the Knoop Indenter or 136° diamond pyramid indenter for testing thin sheet metals is logical. Sheet metals down to 0.001 in. may be tested. Fig. 108 shows two indentations on a flat wire 0.009 in. wide and 0.003 in. thick, tested with a load of 300 grams. Reducing the load to 100 grams would permit testing much thinner material.

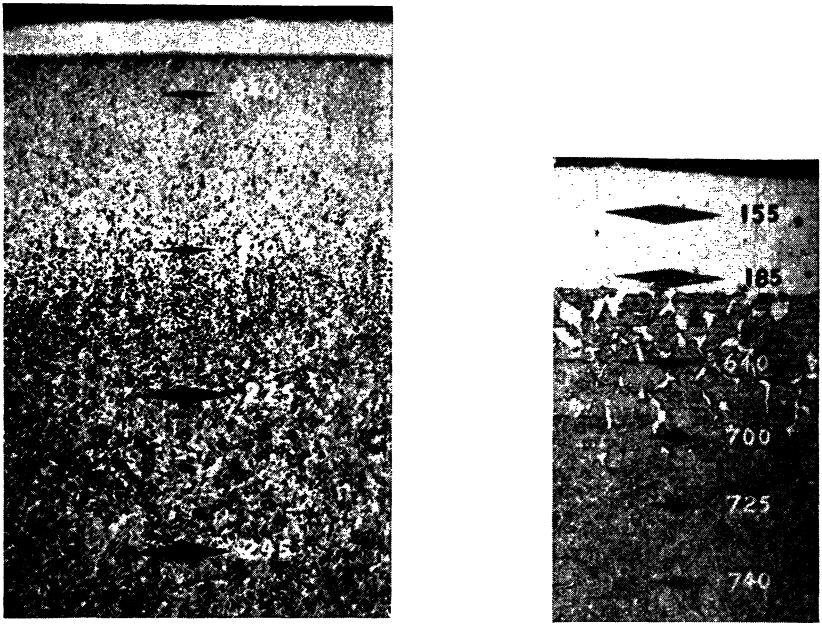


Figure 107. Knoop hardnesses on induction-hardened steel part (75X mag.). *Left:* the hardened case. The indentations are 0.010 inch apart. Load 500 grams. The white surface layer is chromium. *Right:* the decarburized layer. This resulted from austenizing in improperly deoxidized nitrogen. The indentations are 0.005 inch apart. Load 500 grams.

Bimetals in relatively thin strip form made up in two layers, the thickness of each individual layer being as low as 0.0015 to 0.002 in., are tested for the hardness of each component in routine testing in an inspection department.

Microhardness may also be used to study cross-sections of thin material. Fig. 109 shows the variation in hardness across a section of

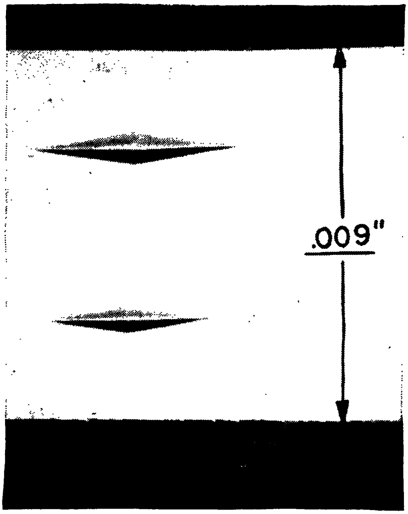
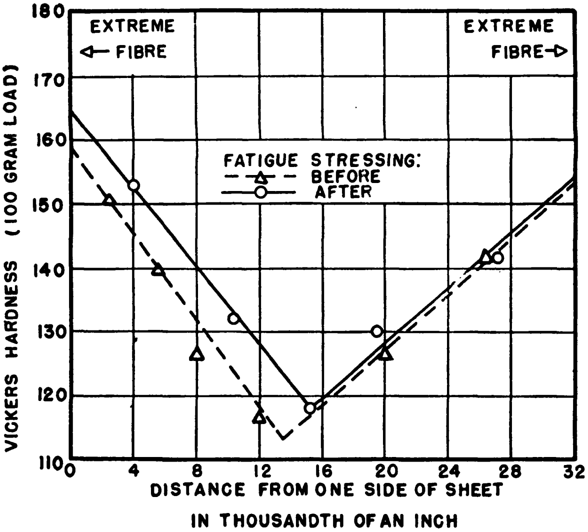


Figure 108. Knoop indentations (250X mag.) on flat wire 0.009 inch wide. Indentations made with load of 300 grams.



(*From Bell Telephone Record*)

Figure 109. Variation in hardness across section of sheet metal .032 inch thick.

annealed copper-beryllium alloy only 0.032 in. thick. The higher hardness at the surface may be explained as due to a light rolling operation used to flatten the sheet. It is to be noted that fatigue stressing did not appreciably change the hardness.

The use of the Tukon tester is a very helpful method of evaluating the work-hardening of small-gauge wires. Hardnesses taken transversely or on a cross-section are very reliable indicators of the degree of cold work and accompanying tensile strength.

Investigations of hardenable steels and nonferrous alloys, when subjected to resistance welding, serve as an example of the use of the Knoop indenter for surveying small areas. A suitable section is prepared by the usual polishing methods and a precise hardness exploration can be made at intervals of approximately 0.002 in. across the entire heat-affected area.

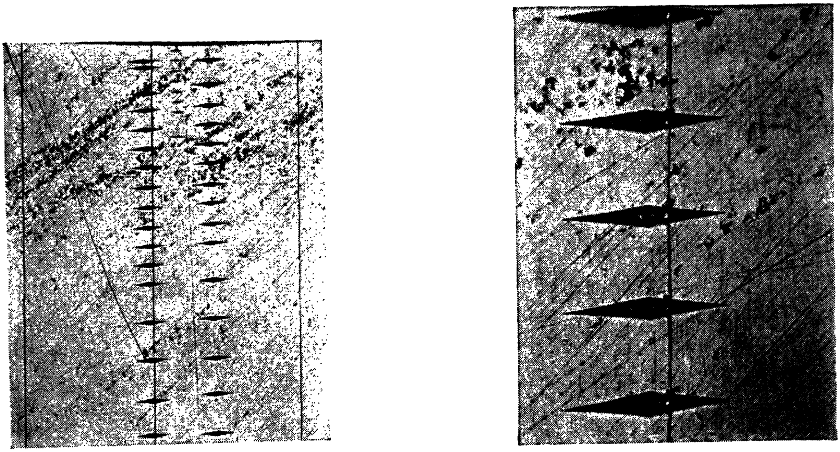
The hardness gradient in the welding of metal caused by difference in temperature, from room temperature to melting temperature, extends from 1/4 to 1 in., depending on the size of material welded. The structural change can be readily correlated with hardness over the entire heat-affected zone.

A transverse section of a ball-bearing raceway is shown in Fig. 110 (left) at × 50, and the table gives the Knoop hardness number (K) with converted Rockwell C scale values. The indentations are spaced at 0.002-in. intervals below the race surface. Of particular interest is the micrograph at the higher magnification (right) × 500. The scratch is made with the Michrocharacter and the readings are also shown. It is obvious from this illustration why the indentation test is preferred to the scratch test, insofar as ease of determination of the measurable value is concerned.

Another example of survey of small areas is the hardness change in hard steel resulting from grinding burn. Sufficient work has been done with the Tukon tester and Knoop indenter to know that they offer a reliable and desirable method for a quantitative study of burn.

Fig. 111 is a hardness gradient curve used in a preliminary study of burn. The indentations were staggered in six columns to permit close spacing of the points on the graph without causing the indentations to interfere with each other. In this case, the surface of steel was softened. Had the grinding operation been more severe the surface itself might have been rehardened, the underlying layer again being soft on account of tempering. Etching in metal would reveal the exact extent of rehardening and the hardness measurements would confirm that rehardening took place.

It should be emphasized that this hardness gradient curve is repre-



Distance Below Race Surface (inches)	Scratch (width in microns)	Knoop Hardness	RC
.002	2.17	791	63.3
.006	2.45	730	60.8
.008	2.33	742	61.1
.010	2.65	688	59.1
.012	2.58	759	61.6
.014	2.52	813	63.3
.016	2.52	811	63.3
.018	2.12	824	64.0
.020	2.12	824	64.0
.022	2.17	822	64.0
.028	2.12	822	64.1

Figure 110. Microhardness tests (Knoop and Scratch) in transverse section of ball bearing raceway. 500 gram load on "Tukon" hardness tester. *Left:* 50X mag. *Right:* 500X mag.

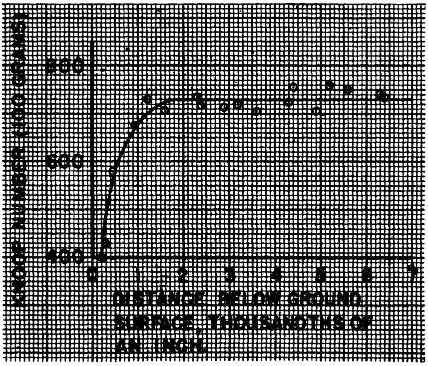


Figure 111. Knoop hardness gradient, 100 gram load, in cross section of hardened tool steel that was ground too severely. Hardness of steel is RC 60.

sentative of poor grinding practice. Much work remains to be done in a detailed and systematic study of burn, but one method of approach is cited.

An entirely different application of the microhardness testing is found in the work of Zlatin and Merchant of Cincinnati Milling Machine Co.[6] They studied the hardness of sections taken through chips and machined surfaces obtained under various machining conditions. It was found that steels may be very severely hardened by the cutting process, increases in Knoop Hardness of as much as 300 per cent having been observed. Under certain conditions the fragments of built-up edge shed along the path of the tool on the finished surface were found to be comparable to the cutting tool itself in hardness. Fig. 112 shows indentation in chips used for this study.

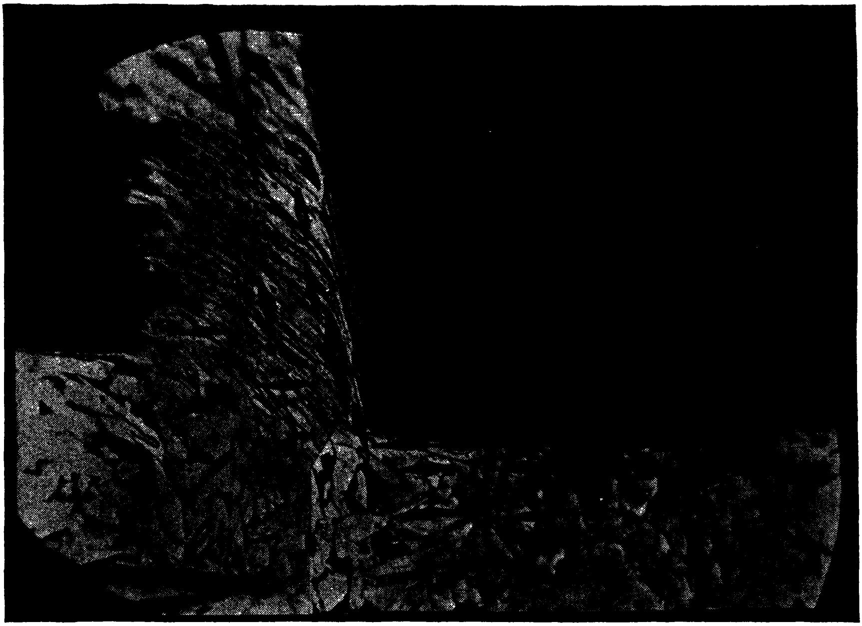


Figure 112. Hardness distribution in milling chip (250X mag.).

These microhardness tests are a useful aid in analyzing the machinability behavior of a metal and in correlating that behavior with the physical properties of the material, with the hope that eventually one may be able to predict the machinability of materials from simple measurements of their physical properties.

When using the microhardness test for identifying or studying individual constituents of a microstructure, either the Knoop Indenter or the 136° diamond pyramid indenter may be used, depending upon which shape is more appropriate. A few typical examples will be discussed.

One instance where the Knoop indenter proved of value was in deciding that a very thin lens of what appeared to be martensite was indeed martensite. At the Ontario Research Foundation, Toronto, where this problem came up, it was possible to place a Knoop impression right on the lens of hard materials. The length of the Knoop impression extended over almost the entire width of the lens, as can be seen from Fig. 113. The lens seemed likely to have been the cause of the failure of the part in which it had formed during the butt-welding operation. These tests were made at 100-gram load and the picture is at × 500.

(Courtesy Ontario Research Foundation, Toronto, Canada)

Figure 113. Knoop indentations in lens of martensite. 100 gram load (500X mag.).

Fig. 114 at × 500 is the structure found adjacent to a crack in a cast-iron ingot mold. The Knoop hardness number in the white constituent (probably Fe_3C) is 1390 at 100-gram load. The hardness of the pearlitic ground mass varies from 290 to 327.

Fig. 115 illustrates an experiment of the Landis Machine Co. with hard spots encountered when milling high-speed steel. It was learned that the hard spots were primarily the result of tremendous heat locally developed by a tool that had failed. The metal being cut would "load" or build up in the chipped area and insulate it against the coolant. Local heat developed in certain cases appeared to have reached an estimated temperature of about 2000° F. The photomicrograph, taken at

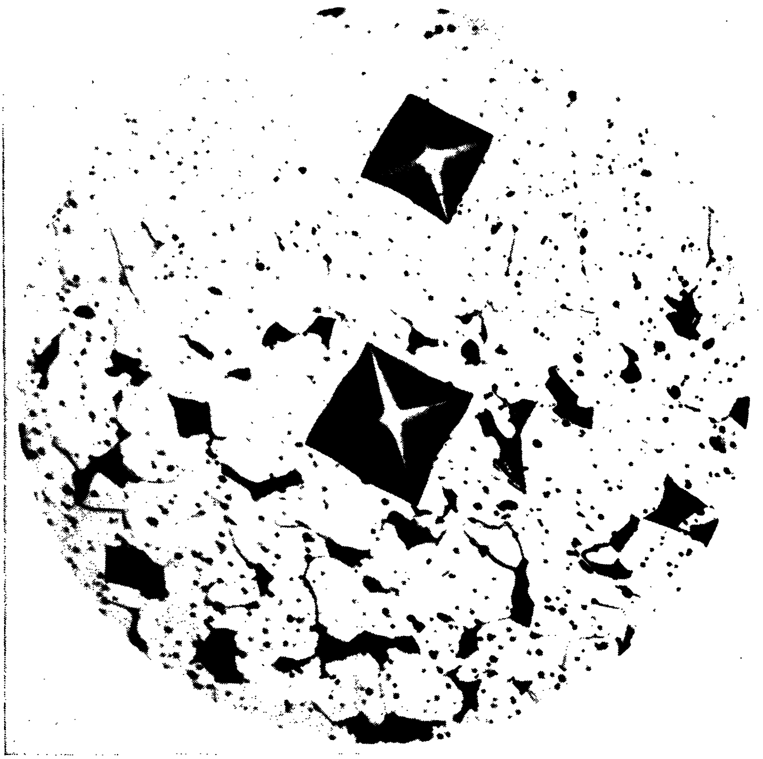
(*Courtesy Ontario Research Foundation, Toronto, Canada*)

Figure 114. Knoop indentation in cast iron ingot mould. 100 gram load (500 *mag.*)

Figure 115. Photomicrograph of a hard area in an 18–4–1 annealed high-speed steel tool (100X *mag.*).

× 100, shows the flow lines developed as a result of a dull tool, and also the martensitic nature of the hard area.

Microscopic and microhardness tests in this instance were quite helpful in arriving at a conclusion which at first seemed unreasonable. The



(From Bell Laboratories Record)

Figure 116. Vickers indentations in a diffusion layer of iron-aluminum alloy (*top*) and in low carbon steel base material (*bottom*). Hardness of diffusion layer is D.P.H. 200, while that of low carbon steel is D.P.H. 120 (500X *mag.*).

Knoop hardness value determined under a load of 500 grams, beginning with the non-segregated area, was 247, and increased, approaching the hard spot, to 393, 398, 403, 422, 473 and 597. A value of 728 was obtained in a part dark streak and light area. By reducing the load to 200 grams, values of 762 were obtained in the white area between dark streaks, and 825 in the white area. The Brinell hardness number of this steel was 228.

E. S. Greiner[7] has determined the microhardness of specific areas in a specimen of low-carbon steel impregnated with aluminum (Fig. 116). The diffusion layer (near top) is an iron-aluminum alloy with a diamond pyramid value of 200. The low-carbon steel has a value of 120. Both values were determined with a load of 200 grams using the Tukon tester.

Fig. 117 by the same investigator shows how microhardness testing may be applied to determine the hardness of structural areas in a lead-antimony alloy. The light-colored area consists of nearly pure lead and large particles of antimony. This section has a Knoop value of 5. The darker area is a solid solution of antimony in lead with a Knoop hardness of 10. Both determinations were made using a load of 25 grams on the Tukon tester.

(From Bell Laboratories Record)

Figure 117. Knoop indentations in lead-antimony alloy, light colored material has a hardness of Knoop 6, while that of the darker colored material is Knoop 10 (250X *mag.*).

Fig. 118 is a photomicrograph of cold-drawn steel with the hardness of constituents indicated.

Two excellent uses of microhardness testing for measuring hardness at the cutting edge are illustrated. Fig. 119 shows how the teeth of a saw close to the cutting edge may be tested. The teeth of the saw are interlaced to prevent rounding of the edges in polishing the sample. Fig. 120 shows micro-indentations made in the transverse web and shank sections of two #80 drills (0.0135 in.) mounted in steel and plastic. The steel (light area) is used in the mounting to prevent rounding of the edges in polishing.

Fig. 121 is a comparison of indentations made with Knoop and 136° diamond pyramid indenters under loads of 3000, 1000, 500 and 100 grams on steel of approximate hardness 550 (1000-gram load). For a given load, the 136° indenter penetrates about twice as far into the specimen as the Knoop indenter, and the diagonal will be about ⅓ the length of the Knoop indentation. Thus the 136° diamond pyramid test is less sensitive to surface conditions than the Knoop test, and for equal loads the diamond pyramid indentation, because of its shorter length, is more affected by errors in measuring the indentation.

It is always of interest to compare hardness values of different materials. A tabulation of hardness values in cutting tools and gauge materials is presented in Table 8, prepared by Mr. d'Arcambal of Pratt & Whitney Co., West Hartford, Conn.

Table 8. Hardness Values on Cutting Tools and Gauge Materials

Name	Rock. A	Rockwell C Equivalent	Knoop Hardness Numbers 1000 g Load
Carbon tool steel	84.5	66	859
Chromium plate (.004″ thick)	82.5	62	882
High speed steel	83.5	64	842
Tantung G	81.5	61	668
Tantung G–2	83.5	64	817
Rexalloy	82	61.5	747
Firthaloy H–13	88.5	73	1368
Firthite T–41H	90	76	1482
Carboloy No. 78B	91	78	1482
Carboloy No. 44A	91	78	1645
Carboloy No. 883	91.5	79	1757
Carboloy No. 999	93	82	2017
Synthetic sapphire			1924
Norbide	95	86	2600
Glass			511
Diamond			5500–7000
Rexalloy	Hard constituent		1134
Rexalloy	Matrix		695
Tantung G	Hard constituent		1022
Tantung G	Matrix		758

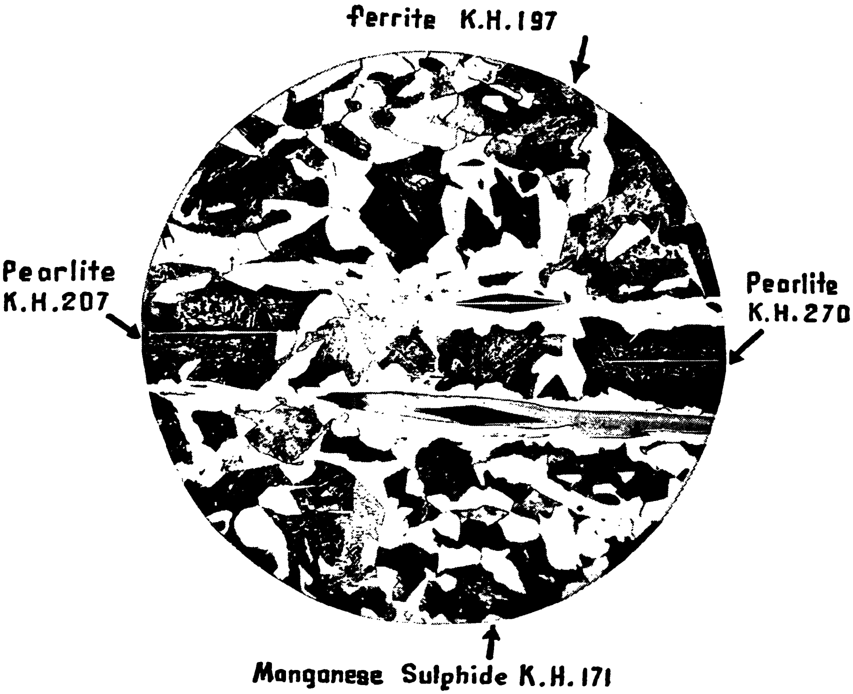


Figure 118. Knoop indentations in constituents of cold drawn steel (400X *mag.*). Load 25 grams.

Figure 119. Knoop indentations in hack saw blade teeth, 24 teeth per inch (40X *mag.*).

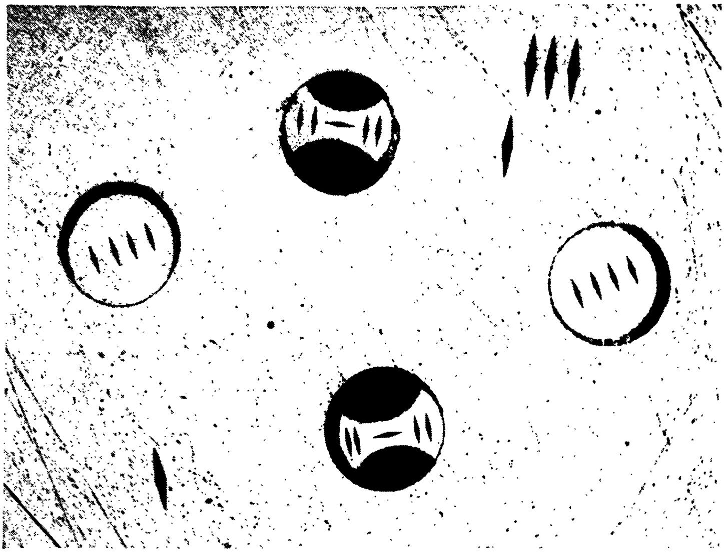


Figure 120. Knoop indentations in #80 drills mounted in steel and plastic (40X *mag.*).

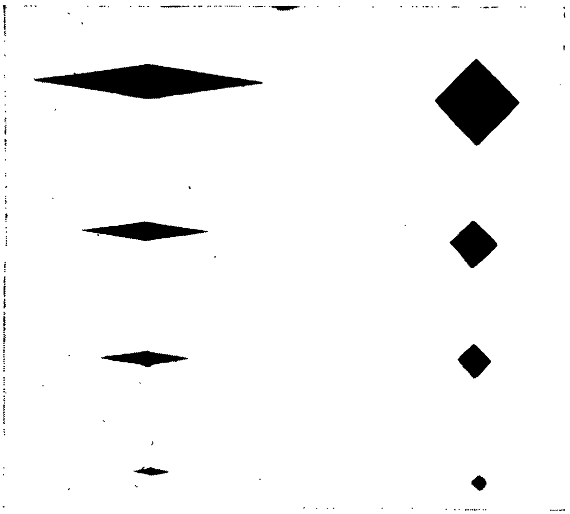


Figure 121. Comparison indentations Knoop and 136° pyramid under load 3000, 1000, 500 and 100 grams.

Limitations of Test

The most serious handicap in microhardness testing is the necessity of properly prepared samples. They must be lapped plane, be free from scratches and so mounted or supported that the indenter is normal to the testing surface. These requirements mean considerable time must be spent in preparation of samples. Often it is necessary to mount the sample, and the usual metallographic polishing methods are employed. Rounded corners will produce areas where accurate tests cannot be made. Great care must be taken in preparing surfaces to minimize cold-working of the surface. The lighter the testing load the more highly polished surface is necessary. With reference to asymmetry of indentation, the length of the shorter portion of the long diagonal of an indentation should be at least 80 per cent of the length of the longer portion. The spacing of the indentations should be about 1.5 times the indentation length. Such spacing is on the conservative side.

Loads lighter than 25 grams are not used with the Tukon tester. The accuracy of indentation measurements is about 1 micron, *i.e.*, ± 0.5 micron. On hard steel, using a load of 25 grams, with the Knoop indenter, the length of indentation is about 20 microns. A difference in determination of length of 1 micron represents a 5 per cent difference in measurement, or about 10 per cent difference in Knoop number. With the 136° diamond pyramid indenter, the length of indentation under 25 grams is 7 microns. Thus a difference in length measure of about 15 per cent is present, if the variation in length determination amounts to 1 micron. This is a difference of from 825 to 1100 in DPH numbers. For qualitative work, tests made with lighter loads may be of value.

It can be seen from the above that exceptionally shallow depths and hardness gradient determinations should be made with the Knoop indenter where the ratio of long diagonal to short is 7:1 and depth of indentation is $\frac{1}{30}$th of the long diagonal. The 136° diamond pyramid indenter may have an advantage where circular or rectangular constituents are being tested or an average value desired. The depth of indentation of this indenter is $\frac{1}{7}$th the length of the diagonal.

Tests made with loads under 25 grams (and possibly from 25 to 100 to a lesser extent) are subject to the following possible sources of considerable error. The first is the influence on the surface hardness due to surface preparation. When the depth of indentation is only of the order of 1 or 2 microns, it is almost impossible to prepare the surface without seriously affecting the outer first micron.

Friction during penetration of the indenter becomes important when extremely light loads are applied. The rate of applying the load is of extreme importance. Results are comparable only when these factors are controlled, and comparisons of microhardness results with light loads will vary with method and rate of load application.

Another variable with extremely small loads is the effect of "sinking" and "ridging" of the impression in the 136° diamond pyramid indenter (under 25 grams). With light loads, it is practically impossible to determine the length of the diagonal, and a small error due to the fact that the surface is disturbed even at the corners of the diagonals introduces serious error in the results.

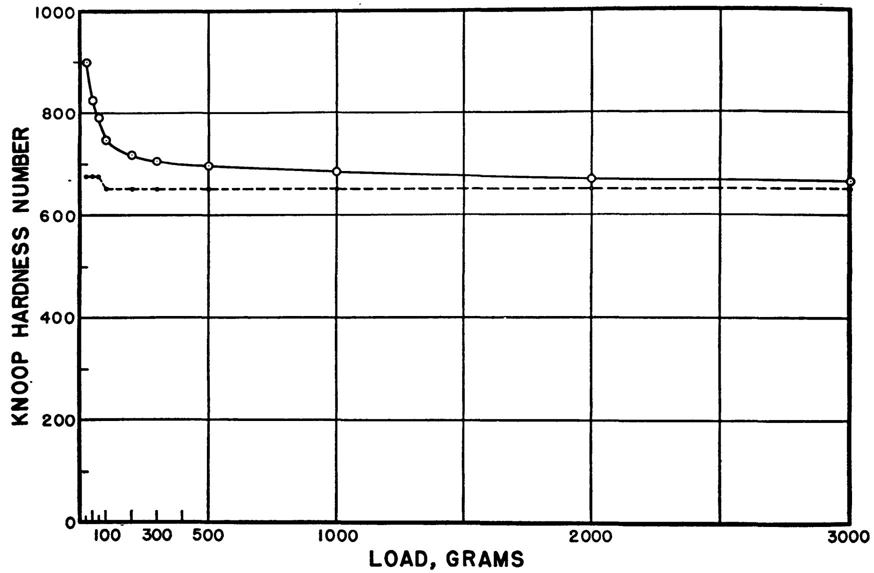


Figure 122. *Solid line:* increase in Knoop number for hardened steel with decreasing load. *Dotted line:* results corrected for elastic recovery and visibility as determined by Tarasov and Thibault.

In the original paper on the Knoop indenter,[1] the authors assumed that the elastic recovery of the long diagonal could be considered negligible, and they defined the Knoop hardness number as relating the applied load to the unrecovered projected area. It was quickly discovered, however, that the lower the indenting load, the greater the Knoop number. This was attributed by D. R. Tate[8] to elastic recovery of the long diagonal upon removal of the load, the recovery being a larger percentage of the length at light loads than at heavy loads. This apparent increase in hardness for a hardened tool steel of Rockwell hardness C601/2 is shown in Fig. 122 (solid line). Much study and checks have been made to determine the cause of this increase. This work may be summed up as follows:

Both elastic recovery of the long dimension of the indentation and the inability of the observer to locate the actual ends of the indentation have the effect of giving a high hardness number from readings observed under the microscope upon removal of load. The indentation length as determined is short by several microns. The inability of the operator to locate the ends of the impression depends on the optical equipment used and the visual acuity of the observer. For hardened tool steel Tarasov and Thibault of Norton Co.[9] have determined the elastic recovery as 0.7 micron and the visibility correction 2.4 microns with a 4.1 × dry objective. This total correction of 3.1 microns, when added to the length of the indentation, gives a result as shown in the dotted curve in Fig. 122. More work is now being done along this line and it is hoped that a complete answer to this will soon be known.

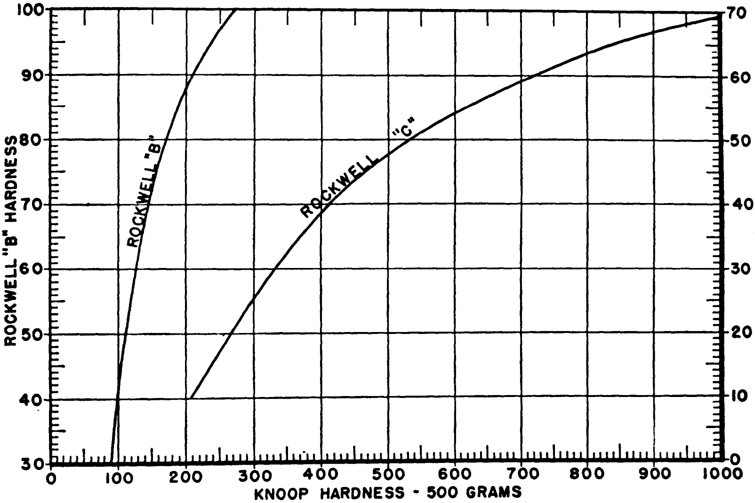


Figure 123. Relation between Knoop hardness and Rockwell B and C scale hardness.

This, however, does not detract from the value of the test. Even on homogeneous materials, Knoop hardness numbers should not be reported unless the load at which the determination was made is likewise reported. Only when one is certain of the related facts should comparison be made with results obtained with different loads.

Martin and Wiley[5] have presented a conversion chart (Fig. 123) showing the relation between Rockwell C scale and Knoop numbers, using a load of 500 grams. Shown in the curve is a chart by Shubrooks[10] for the relation for the B scale of the Rockwell tester. Such charts are of value in acquainting the user with Knoop numbers in terms of a scale with which he is familiar. They should never be used to set specifications or to meet specifications, nor should they be considered for Knoop numbers obtained with loads under 500 grams.

The use of the microhardness tester for materials other than metals is discussed in the next chapter.

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Chapter XVI

Indentation Hardness Testing of Non-metallic Materials

The hardness testing equipment discussed previously was designed for testing the hardness of metals. As might be expected, the success of the testers used for controlling the hardness of metals stimulated a desire to use the same instruments for testing non-metallic materials. Some of the testers have been used to a certain extent for such purposes and their use in this field will be discussed.

No attempt will be made to describe the many tests devised for controlling the hardness of non-metallic materials in cases where the instrument was designed solely for such purposes. There are a multitude of such instruments, running all the way from equipment for testing timber and wood base materials to even a special machine used for testing the hardness of chicken grit. In most cases each has a very limited application. Many modified tests are also used as, for example, a modified Rockwell test employing a 1-in. diameter steel ball and major load of 60 kg, is used by Du Pont De Nemours Co. for testing the hardness of resin impregnation of wood. Here again each modified test has generally only a limited application.

Rubber is tested to a considerable extent for hardness, but usually either by the Durometer or according to the American Society for Testing Materials' Specification D 314. The latter method merely subjects the material to a definite pressure (3 pounds) by an indenter (0.0938-in. diameter ball) under definitely prescribed conditions, and measures the indentation.

The Shore Durometer (Fig. 124) consists of a beam type weighing scale and a compressor pin. As the pin indents the rubber, the beam works against a resistor spring and the pin movement is measured by a pointer on a dial indicator scale.

Fundamentally, however, it is not the purpose here to discuss the various means of testing non-metallic materials, but rather to review the application of well-known metal indentation hardness testers in the field of non-metals.

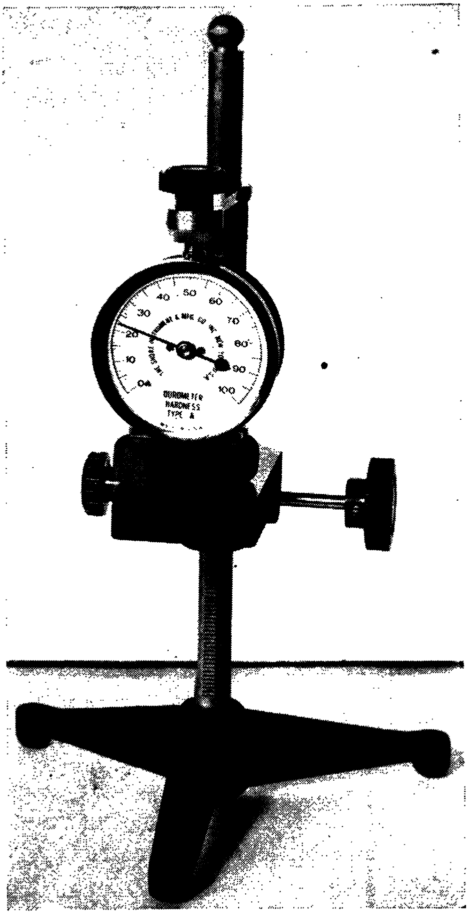


Figure 124. The Shore Durometer.

(Courtesy The Shore Instrument & Mfg. Co., Inc., Jamaica, New York)

Plastics

The use of indentation as a quick, non-destructive index of physical properties is widespread in the plastics industries. Plastics include a considerable hardness range, from the soft grades of cellulose acetate to the harder urea and melamine materials. Indentation hardness tests are of value in correlating such properties as punching, machining, buffing and sometimes mechanical wear resistance of plastics; also, they serve as routine check in controlling manufacturing processes and serve as a quick, non-destructive test of identity. Compressive and possibly tensile moduli may be indicated approximately from the hardness test. As plastics are used more and more for bearings, gears, elements of construction, etc., the need for determining hardness becomes more vital. With some thermoplastics hardness may be related to resistance to softening with increase in temperature.

It should be pointed out that indentation hardness tests on plastics should not be used as a substitute for the scratch hardness test. Ability to resist scratching is an important property in some plastics, since the ease with which many plastics are scratched is a serious disadvantage in their substitution for other materials as, for example, in substituting transparent organic plastics for glass. Plastics vary considerably in scratch resistance, and the Bierbaum Microcharacter is the most widely used instrument for measuring this property. This test has been described previously.

It may not be amiss to inject here that for those not in a position to make the Microcharacter test, a rough but simple method of classifying the scratch resistance of plastics may be obtained from the use of a series of 13 drawing pencils (high-grade) numbered 2B to 9H. The sharp point of the pencil is drawn across the polished surface of the sample under pressure. If the plastic is harder than the pencil carbon, the point will be broken down; if the pencil is harder than the plastic, a groove will be formed in the surface.

Another simple method of obtaining the relative scratch resistance of two materials is to scratch the surface of one material with the corner of the other. Both these tests may require considerable practice to develop the proper technique. The pencil measurement range may be extended by using special pencils made from alloys of pure lead and antimony.

The indentation hardness tests used for determination of the hardness of plastics include the Brinell, the Rockwell method, the Rockwell superficial method, 136° diamond pyramid test, Knoop and the Scleroscope. In these tests, with the exception of the Scleroscope, equilibrium may not be reached upon applying and removing the load in the usual manner. In fact, in some cases, due to size of load, shape of penetrator and resistance of the plastic to indentation, the penetrator would continue to indent the material indefinitely. To obtain reproducible results, it is essential that the exact time the load is applied to the material be specified.

Furthermore, as the indentation hardness of plastics may vary to a considerable extent with temperature and humidity, all samples should be properly conditioned as, for example, by A.S.T.M. method D 618. This calls for a temperature of 25° ± 2° C and 50 per cent relative humidity.

Typical results obtained on plastics with the Tukon tester and Knoop indenter are shown in Table 9 covering different grades of cellulose acetate butyrate.

Table 9. Knoop Numbers on Different Grades of Cellulose Acetate Butyrate Molding Composition

Grade	Knoop Hardness Numbers From Long Diagonal	 From Short Diagonal
205H$_4$	8.8	13.3
205H$_2$	7.2	8.7
205M$_H$	6.2	7.4
205M$_S$	4.9	5.7
205S$_3$	4.3	4.7
205S$_5$	3.3	3.6
239S$_6$	1.9	2.2

Table 10 shows the change in Knoop numbers with load and with thickness. These values were not determined under controlled temperature and humidity and therefore are comparative only. Any anomalies in the results may be due to lack of conditioning of the samples.

Table 10. Knoop Numbers Obtained under Different Loads on Different Thicknesses of Cellulose Acetate Butyrate Molding Composition

Applied Load, g	Knoop Hardness Numbers ¼ in. Thick	 ⅛ in. Thick	 1/16 in. Thick
	Specimen 239 S$_6$		
50	1.8	1.9	1.9
100	1.9	1.9	2.0
300	1.9	1.9	1.9
	Specimen 205 H$_4$		
50	9.2	9.0	9.1
100	9.0	8.8	8.8
300	9.5	8.5	8.6

Fig. 126 shows Knoop indentation in a transparent cellulose acetate sheet. For measuring the length of indentations in transparent material, vertical illumination and the highest N.A. objective possible, is recommended. The use of phase contrast microscopy, which is now receiving the attention of microscope manufacturers, may be advantageous in determining the length of the indentation in transparent materials.

Rockwell Hardness Test

The Rockwell hardness tester is the most widely used instrument for measuring the hardness of plastics. Most of the tests are carried out following the procedure of the A.S.T.M. (Designation D 785). It should be pointed out here that the Rockwell hardness tester was designed for testing metals where the amount of recovery of the metal, upon removal of the major load, is small in proportion to the total depth of penetration. With plastics, on the other hand, the amount of recovery of the material is large in proportion to the total indentation. With plastics having elastomeric characteristics, it may be that the results of the Rockwell test, taken in the usual manner, may not be of any value, since the recovery is so great in proportion to the total indentation. Methods for obtaining indentation index on the Rockwell tester, with the major load applied, are described later.

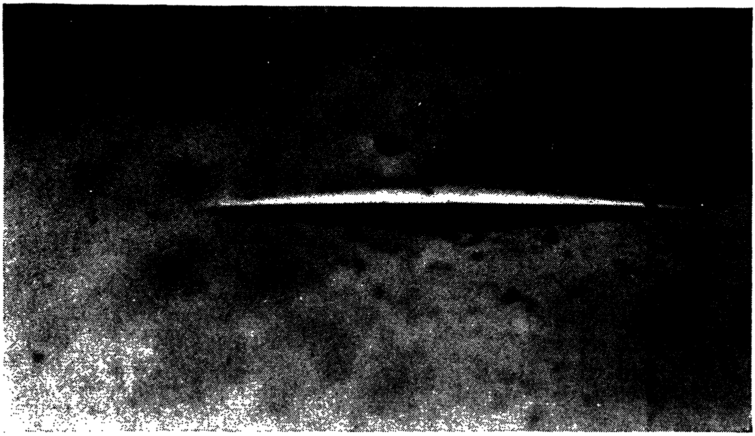


Figure 126. Knoop indentation on cellulose acetate (125X mag.).

In making a Rockwell test in the conventional manner, there is a certain amount of spring in the frame as the major load is applied. This may be observed on the dial gauge, and since it is an upward movement of the frame, with respect to the plunger rod holding the penetrator, it registers on the dial gauge in the same direction as penetration into the material being tested. After the major load is removed, the spring of the frame, caused by the application of the major load, is recovered; this factor does not enter into the reading, because the gauge dial is set at zero before the application of the major load and the final reading is taken upon removal of the major load.

The spring in the frame depends upon the design of the tester and the major load applied. Various models of the Rockwell tester have different values for the spring in the frame, and each machine of a given model may show a different value. This value will also vary with different vertical capacities. It will be constant for any one machine for a given load and a given penetrator. It may be readily determined in terms of dial gauge divisions by making a test in the usual manner, *i.e.*, by applying the minor load, setting the dial gauge at zero and applying (but not removing) the major load. Under this condition, the gauge indicates the total relative movement of the plunger and the frame, and includes depth of penetration into the material, the spring of the frame, penetrator and plunger system holding the penetrator, and the elastic deformation of the material under test. Without removing the piece being tested, the complete operation, including applying the minor load and setting the dial to zero or "Set," is repeated until the movement of the dial gauge becomes constant; then only is the spring of the frame, penetrator and the elasticity of the metal sample indicated. If material such as soft copper is used as a sample, the elastic recovery of the metal is negligible and the value on the dial gauge represents the spring of the frame for practical purposes.

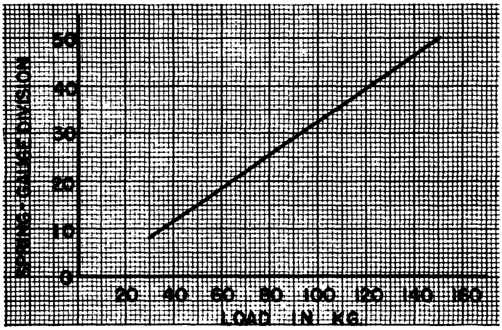


Figure 127. Curve showing representative spring of frame on 3JR Rockwell hardness tester.

Fig. 127 shows typical values for the spring in the frame for different loads in a current 8 in. capacity Rockwell tester. This curve represents the deflection in addition to the deflection produced by the minor load.

For metals, excluding shapes such as tubes, the movement of the dial gauge due to the elasticity of the metal under test is small and may be considered of no disadvantage when making the test. With plastics this elasticity may reach considerable proportions; when acting in addition to the spring of the frame of the tester, it may prevent full application of the major load due to limitations in the design of the tester, which are governed primarily by the requirements for testing metals. It is a safe assumption to consider the limitation of the standard model Rockwell tester as 150 dial gauge divisions under a load of 150 kg. This figure represents the number of divisions of travel of the dial gauge due to penetration into the material under test, spring of the frame, penetrator and plunger rod system, and elasticity of the material under test, while the major load is applied.

Special Rockwell testers designated as PL models increase this limitation to 250 divisions under a load of 150 kg.

To determine whether or not the machine limitation is exceeded and whether the major load is fully applied, simply apply the major load in the usual manner. With the major load still acting, apply an additional load by hand pressure on the weights on the machine; the dial gauge needle then should indicate additional penetration. If not, the full major load may not be acting (due to reaching limit of depth of indentation) and faulty readings may result.

Most plastics are time-sensitive so far as hardness is concerned. When tested by the Rockwell method, the time factor must be considered at three different places in the test.

After the minor load is applied, there may be creeping of the needle of the dial gauge when testing soft plastics. If the major load is applied *immediately* after the dial gauge is set at zero, it is not necessary to apply a time factor with reference to the minor load. It is desirable, however, to specify some time as, for example, 10 seconds, as the interval within which the minor load is applied and the zero setting made.

The time of application of the major load must be controlled carefully if reproducible results are to be obtained. The results of many tests on plastics of different hardness indicate that a loading time of 15 seconds is satisfactory. This time interval starts when the major load is applied (lever tripped) and ends when the load is removed. It includes, therefore, the time for applying the load, as determined by dashpot control valve setting, as well as the time during which the full load is applied and creep occurs. A shorter time interval than 15 seconds may result in the removal of the major load while the dial gauge needle is moving quite rapidly; moreover, a longer time interval unnecessarily lengthens the time required to make the test and makes the time for cold flow needlessly long for some plastics. Reproducible results may be readily obtained, if the loading time of 15 seconds is maintained, to an accuracy of ± 1 second. It is obvious that when creep occurs there is no single time interval which necessarily results in a "true" Rockwell hardness number, and the 15-second interval has been agreed upon as a compromise to effect economy of time and reproducibility.

Fig. 128 shows the effect of loading time on a hard, medium and soft plastic using a load of 100 kg and a ¼ in. diameter ball penetrator. The time of application of major load varied from 7 to 20 seconds. The readings were observed 15 seconds after removal of the major load.

The final time factor to be considered is the interval after removing the major load at which the Rockwell number is observed. Here again 15 seconds has been found satisfactory. There has been a tendency to stretch this time factor to 45 seconds, but this unnecessarily delays the time required to make the test, without any appreciable gain. This factor is not as sensitive as the time factor for applying the major load.

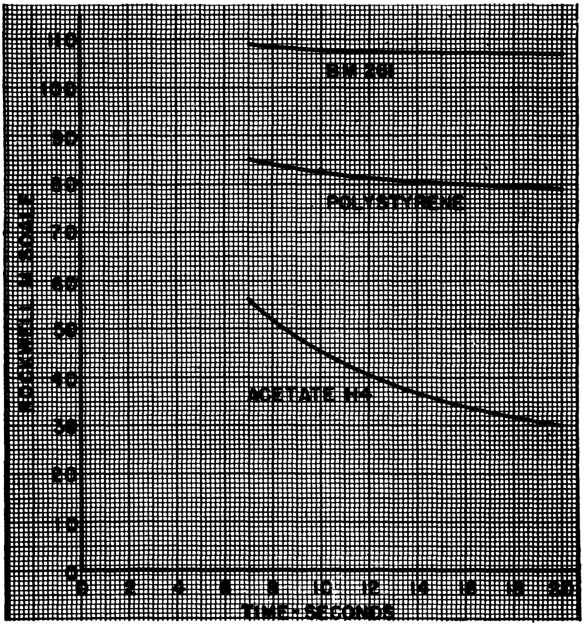


Figure 128. Effect of length of time for applying major load. Reading taken 15 seconds after removing major load.

Fig. 129 shows the effect of time of reading on plastics at different hardnesses after removal of major load. The major load was applied for 15 seconds.

The penetrators generally used for testing plastics are the 1/8, 1/4 and 1/2 in. diameter balls and the loads are 60 and 100 kg. The scales are the E, L, M and R. While some slight advantage might be gained by use of the P and S scales, the scales first mentioned will take care of plastics very nicely from inorganic-filled melamine to soft cellulose acetates.

Table 11 shows the load and penetrator for each of the above scales.

In selecting the proper scale, the limiting range of the machine (150 divisions of penetration for normal and 250 divisions for PL model)

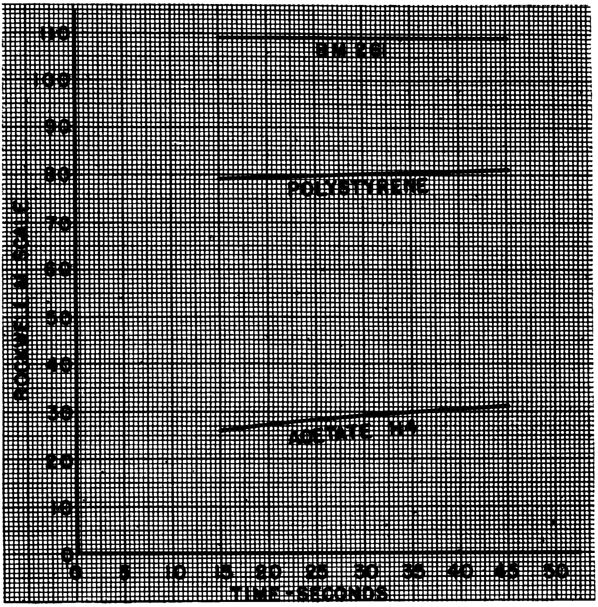


Figure 129. Effect of time of reading after removal of major load; major load applied for fifteen seconds.

Table 11. Scales—Normal Model Rockwell Tester

Scale Symbol	Penetrator	Load in Kilograms	Dial Figures
E	1/8" ball	60	Red
L	1/4" ball	60	Red
M	1/4" ball	100	Red
P	1/4" ball	150	Red
R	1/2" ball	60	Red
S	1/2" ball	100	Red
V	1/2" ball	150	Red

should not be exceeded. If it is exceeded a lighter load or larger ball penetrator should be used.

Readings over 100 are generally not recommended because of lack of sensitivity with such high values. However, in the interest of continuity, and keeping number of scales to cover the plastic range to a minimum, values up to 115 may be permissible.

Following the above precautions, reproducible results to better than ± 1 Rockwell number should be obtained. Seldom (except in the case of laminates) will it be necessary to make more than 3 to 5 determinations to obtain a good average.

The specimen thickness should be 1/4 in. unless it has been ascertained that thinner samples are not influenced by the supporting anvil. It has been found satisfactory to test more than one piece of a plastic to meet the thickness requirement, provided the samples are free from burrs and other protrusions. If more than one piece is used, this should be noted in the results. The material should be supported on a flat anvil. A spot anvil should not be used, as it might act as a penetrator. The samples must be flat so as to seat properly on the anvil. Specimens should be 1 × 1 in., if possible, and never less than ½ × ½ in.

Many variations of the above time cycle will be found in industrial testing of plastics. For example, Rohm & Haas Co. set a time factor of 30 seconds for application of major load, and the readings are taken 30 seconds after the major load is removed. The M scale, *i.e.*, ¼-in. ball penetrator and 100-kg load, is used.

An appreciable difference will result if readings taken with this set of time factors are compared with tests made as outlined in the preceding section. However, if the time factors specified are used, then good correlation will result, *provided* the full major load is applied to the specimen.

Alpha and Beta Scale Tests on Rockwell Tester

In a very complete study of the testing for hardness of plastics by indentation methods, using the Rockwell tester, L. Boor[2] has developed a procedure which permits measurement of indentation depth under the major load. Boor proposes the use of two scales, Alpha and Beta. Reduced to fundamentals, it consists of first determining the spring of the tester for the particular machine and penetrator being used, as described above, and applying minor and major loads to the specimen.

The Alpha scale uses the ½-in. ball penetrator and 60-kg load. The test is made by applying the minor load in the usual manner, setting the dial at zero or "set," and applying the major load (60 kg) for 15 seconds. With the major load still applied, read on the dial gauge how many divisions the penetrator has traveled from zero or "set." From this figure subtract the spring of the tester (determined under major load of 60 kg) and subtract the remainder from 150.

Example: If the spring of the tester is 16 divisions and when testing a plastic the pointer travels 47 divisions (this would mean the pointer is 83 on the red figured scale), then the Alpha scale reading is 47 less 16 or 31, which is subtracted from 150, giving 119 for the reading.

The Beta test is performed in exactly the same manner, except that the major load is 30 kg and the spring of the tester is determined under the major load of 30 kg. As this load is special, the value of the weight applying it may be determined as follows.

It is necessary to make a special weight pan. For the machines having a weight pan weighing 2490 grams, a weight pan weighing 990 grams must be substituted to apply 30 kg. For machines having a weight pan weighing 1849 grams, a pan weighing 649 grams must be used to apply 30 kg. 150 scale divisions were decided as a limit for the test, to make certain that the major load would be applied under all conditions, even when made on regular or PL machines. By subtracting the number of divisions the pointer travels from 150, the scale is reversed so that, in the Alpha and Beta scales, as in all Rockwell scales, the softer the material the lower the hardness number. Since the minor load on the superficial tester is only 3 kg and since the dial divisions represent different values, the Rockwell superficial tester cannot be used for the Alpha and Beta scales (although it has a 30-kg major load).

The Alpha and Beta scales provide a simple indentation hardness test covering the entire range of plastics, based on the unrecovered depth of indentation. This test eliminates residual indentation, such as obtained in the usual Rockwell test, and as the values obtained do not bear any relation to values of indentation obtained upon recovery after removal of major load, there may be some merit in results obtained by this method.

Boor also investigated the application of Meyer's Analysis to plastic materials, determining the Meyer constants from the depth of indentation. However, the results indicated that variation in behavior of plastics under spherical indenters cannot yet be expressed in terms of one or two constants, and a complete study of this nature would require the determination of load depth relations below 30 kg and greater than the 150-scale division limitations.

Recovery after Indentation

In practice there is a method combining the features of both the above. Many users of the Rockwell hardness tester and even the Rockwell superficial hardness tester have found that information secured from recovery of indentation after removal of the major load, in addition to the Rockwell number determined in the regular manner, is very helpful in solving machining problems and controlling the quality of their plastic products. This information has been reported as useful, provided the composition and processing of the material were held to the same specifications. The method of carrying out the test is as follows.

A load and penetrator are selected which will give good sensitivity consistent with the flow and creep of the material. This requirement will determine whether the normal Rockwell hardness tester or the

Rockwell superficial tester is to be used. In general, one selects the heaviest load and the smallest penetrator which give minimum creep and produce an impression which does not show through on the reverse side of the sample underneath the test. The spring of the tester is determined as described above. A time factor is used for the length of time for applying the major load after the release is tripped and, if necessary, before reading the hardness value after the major load is removed.

The test is made in the following manner:

1. Apply the minor load and set indicator at "set."
2. Apply the major load for a definite time interval and record the dial reading with the major load still applied.
3. Remove the major load and record the dial reading again. If a second time factor is necessary, the reading is observed after this selected time has elapsed.

The two readings are then plotted on a vertical line graph. The lowest reading or deepest penetration, that is, the reading taken with the major load applied, is then corrected for the spring in the tester.

As more than one revolution of the dial will occur when testing plastic material, it is recommended that three revolutions, or 300 divisions of the dial gauge, be used as the scale; it is advisable to record all readings on the basis of these three revolutions, making certain that the readings are in the proper revolution of the dial and proper position of the 300-division scale. If in the machine being used three revolutions are not available, two revolutions may be used provided the full load is applied to the specimen.

Fig. 130 shows a sample graph of two materials, A and B, which may have the same value when major load is applied, but a decidedly different value after it is removed. It is possible that the material having the high recovery has certain advantages in some applications, whereas in other applications material with low recovery is desired.

Rockwell Superficial Tester

The Rockwell superficial tester could be used for testing plastic materials and may even offer some advantage over the normal model because of the lighter loads employed. Inasmuch as there are many more normal model testers in use, more work has been done with this model and furthermore some of the advantages gained by use of light loads are offset by a more sensitive depth-measuring system. Basically, the superficial model Rockwell tester was developed for testing thin material, not soft material, and the fact that thin sheet plastic materials may be stacked in making hardness tests has tended to promote the use of the normal model.

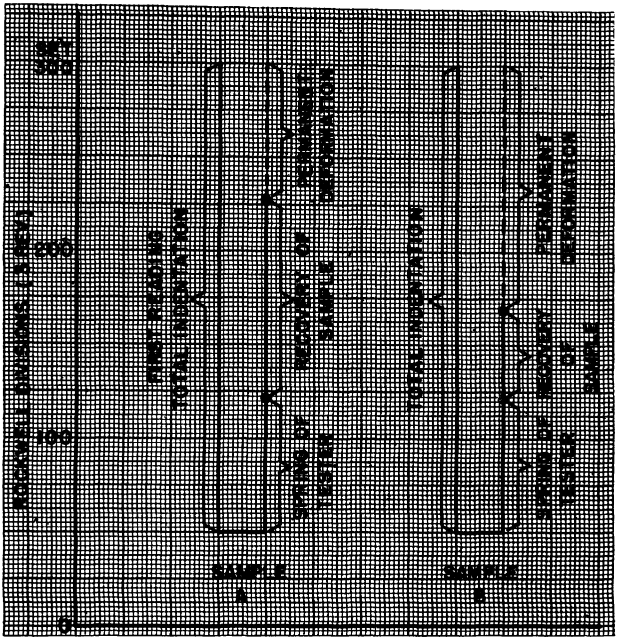


Figure 130. Two materials having same hardness value when major load is applied but different value after major load is removed.

Comparison of Results

Table 12 shows approximate hardness values determined under different hardness testing methods. This table covers typical plastic materials in different hardness ranges, from phenolics to acetates. The materials are listed in the hardness order as determined by the Knoop indenter and Tukon tester under load of 200 grams.

Table 12. Approximate Hardness Values of Typical Plastic Materials

Material	Knoop Hardness Number–200 Gram Load	Rockwell Alpha Scale	E Scale 1/8–100	M Scale 1/4–100	L Scale 1/4–60	R Scale 1/2–60	Bier-Baum Scratch Hardness 3 Gram Load	Scleroscope
Bakelite BM 261	53	128	82	109			21	80
Bakelite BM 120	42	122	88	114			19	85
Polystrene (inj)	17	109		76			10	70
Polystrene (comp)	17	106		79			10	75
Plexiglas II	16	102		97	111		17	80
Plexiglas I A	16	100		88	106		17	80
Fibestos	12	65		49	82		10	70
Ethyl cellulose (MED)	6	43			47	95	6	55
Saran (inj)	4	12			20	78	9	40

It will be observed that there is agreement between this order and the order as determined by the Alpha scale of the Rockwell tester. However, the M scale of the Rockwell tester shows a difference in order of hardness, which is probably due to recovery of the specimen upon removal of the major load. It should be remembered that the long diagonal of the Knoop indentation is but little affected by elastic recovery.

By including values for the E, M, L and R scales of the Rockwell tester, an idea of the sensitivity and overlapping of the scales may be obtained. It must be kept in mind that the amount of recovery will vary not only with the elasticity of material, but also the amount of major load.

Bierbaum scratch hardness values are included to show the order of materials in resistance to scratch and to emphasize that resistance to permanent indentation differs from scratch resistance. As can be seen from the table, even resistance to permanent indentation is restricted to the actual conditions of any one test. Scleroscope values are also shown.

As mentioned previously, resistance to scratch or even mar resistance may be determined by the Tukon tester and the Knoop indenter using a 25-gram load and producing an indentation only a few microns deep. If successful, this would permit the substitution of the more rapid indentation hardness measurement for the scratch resistance measurement and resulting difficulties, such as judging the precise location of the edge of the scratch under a microscope. More work must be done along this line to determine the value of microhardness.

With the greater use of plastics in industry, the hardness test becomes more essential to the user and manufacturer of plastic materials, and provided the test is restricted to measurement of resistance to indentation, it should become a valuable aid to the engineer.

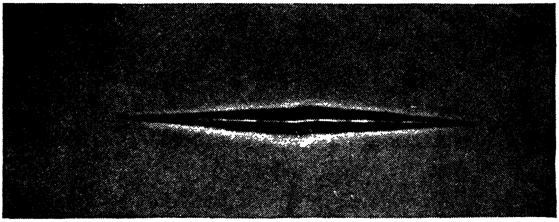
Minerals

Other non-metallic materials which may be tested for hardness by the indentation method are minerals. For this work the Knoop indenter is now coming into use; it permits a quantitative measurement of minerals, ranging in hardness from argentite (Knoop hardness of 25) to diamond (Knoop hardness about 7000). Previous work by scratch methods permitted only a qualitative measurement.

It has been found that crystals vary in hardness with orientation of the test surface and with orientation of the long axis of the Knoop indenter in that surface. In many cases, the importance of the hardness of many minerals is of academic value only; therefore, this discussion will be limited to a few generalities. For a more complete study of the matter, the reader is referred to the work of Winchell[3] and Thibault and Nyquist.[4]

A polished flat surface is required. To correlate the hardness number with orientation of the test specimen and the long axis of the indenter, the orientation should be specified. It might also be helpful to obtain average hardness numbers by making a large number of indentations in random orientation.

In testing brittle minerals, such as glass, topaz, silicon carbide, etc., subsurface and surface cracking may occur. A study of such fractures on hard, transparent, brittle substances, showed that the hardness value is not affected if the cracking is of a subsurface nature, and if the specimen shows no perceptible amount of surface cracking. To minimize this cracking effect, the load should be as light as possible; generally 100 grams is satisfactory.



(Courtesy Norton Company, Worcester, Mass.)

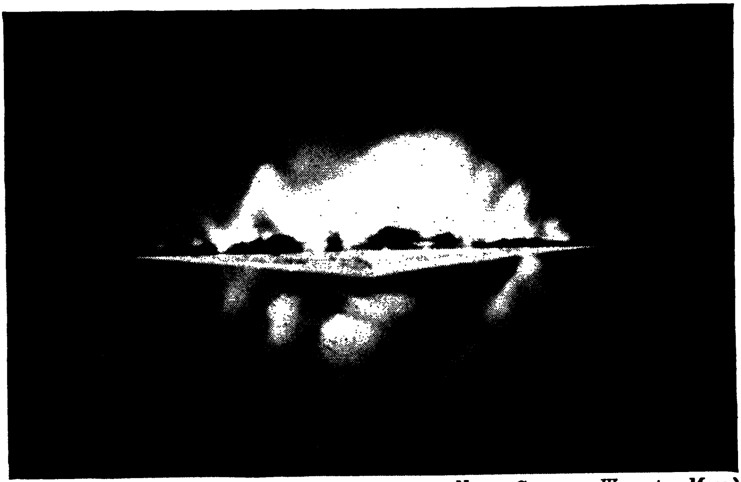
Figure 131. 100 gram indentation in silicon carbide (2000X mag.). Knoop hardness = 2460.

Fig. 131 shows indentation in silicon carbide under load of 100 grams.

Fig. 132 shows moderate cracking produced when load is increased to 300 grams.

As the Knoop hardness number often varies with the load applied on the indenter, comparable results are obtained only if the material is tested with the same load. For minerals, the load of 100 grams is recommended. Under all conditions, however, the load at which the determinations were made should be specified.

The hardness of diamond has always intrigued the engineer. C. G. Peters of the National Bureau of Standards made tests with the Knoop indenter with a load of 500 grams. Indentations were made in plane facets cut parallel to the cube and octahedron, and to intermediate directions of diamonds obtained from various mines in Africa. The range of indentation hardness numbers was from 5500 to 6950 Knoop numbers. Fig. 133 shows a group of such Knoop indentations in diamond at 425 magnifications.



(Courtesy Norton Company, Worcester, Mass.)

Figure 132. 300 gram indentation in silicon carbide. (*Note moderate cracking.*) (1500X *mag.*) Knoop hardness = 2210.

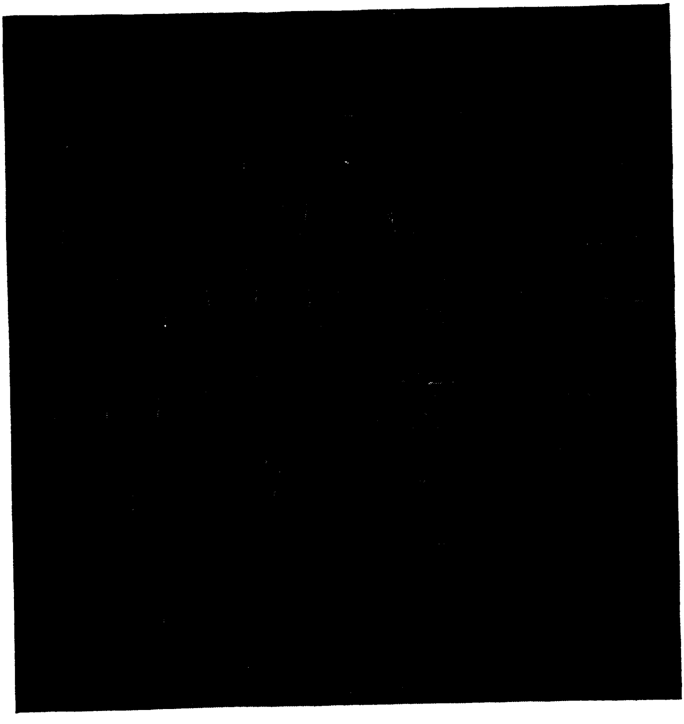


Figure 133. Knoop indentations in diamond, load 500 grams (425X *mag.*).

Table 13 published by Knoop & Peters,[5] later modified, gives Knoop hardness values for minerals and abrasive materials, ranging from gypsum to diamond. The load used was probably 500 grams but lacking this exact value, this table of values is not to be considered for comparison with data from other investigations.

Table 13. Knoop Hardness of Mohs Minerals and Abrasive Materials

Samples	Knoop Numbers
Gypsum	32
Calcite	135
Fluorite	163
Apatite parallel to axis	360
Apatite perpendicular to axis	430
Albite	490
Orthoclase	560
Crystalline quartz parallel to axis	710
Crystalline quartz perpendicular to axis	790
Topaz	1250
Carboloy	1050 to 1500
Regular alundum No. 1	1635
Regular alundum No. 2	1625
Regular alundum No. 3	1620
98-alundum No. 1	1670
98-alundum No. 2	1680
Black silicon carbide No. 1	2150
Black silicon carbide No. 2	2050
Green silicon carbide No. 1	2130
Green silicon carbide No. 2	2140
Molded boron carbide No. 1	2250
Molded boron carbide No. 2	2260
Molded boron carbide No. 3	2250
Diamond	5500 to 6950

Table 14 gives Knoop numbers of various glasses as determined under a load of 500 grams. The brittleness of glass may also be investigated by increasing the applied load until fracture occurs. For example, phosphate glass fractures with a load of 200 grams, whereas lead silicate will stand a load of 1400 grams before fracturing.

Fig. 134 shows an impression in $\frac{3}{16}$-in. plate glass under load of 1000 grams.

Research work may be carried on with the Knoop indenter on minerals. For example, the effect of hardness on grinding and polishing of glass may be studied, as well as the hardness of jewels for bearing purposes. Hardness of enamels and ceramics is being investigated, but as yet the work is not sufficiently advanced to discuss the suitability of the Knoop indenter for such testing.

The injury to enamel and denture in human teeth from a dentifrice containing harsh abrasives may be studied. Work done at the National

Table 14. Knoop Number of Various Glasses

Sample	Type of Glass	Knoop Number, 500-g. Load
No. 1......	Soda-lime-silicate (3/32 in.)	538
No. 2......		531
No. 3......		544
No. 4......	Soda-lime-silicate (3/16 in.)	535
No. 5......		542
No. 6......		536
No. 7......	Soda-lime-silicate (1/4 in.)	518
No. 8......	Soda-lime-silicate (1/4 in.) Heat treated	510
No. 9......		527
No. 10......	Soda-lime-silicate	528
No. 11......	Iron-soda-lime-silicate (with varying iron content)	494
No. 12......		476
No. 13......		445
No. 14......		428
No. 15......	Soda-potash-lime-silicate	540
No. 16......	Barium silicate	546
No. 17......	Lead silicate (with varying lead content)	436
No. 18.......		396
No. 19......		373
No. 20......	Phosphate	517

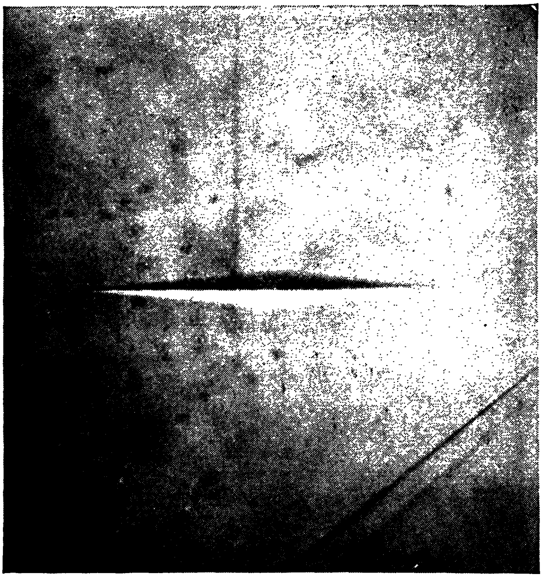


Figure 134. Knoop impression in 3/16 inch thick plate glass, load 1000 grams (400X mag.).

Bureau of Standards on human teeth before and after being subjected to brushing tests, shows changes in surface structures. Impressions made on polished tooth structures are measured before and after the tests and

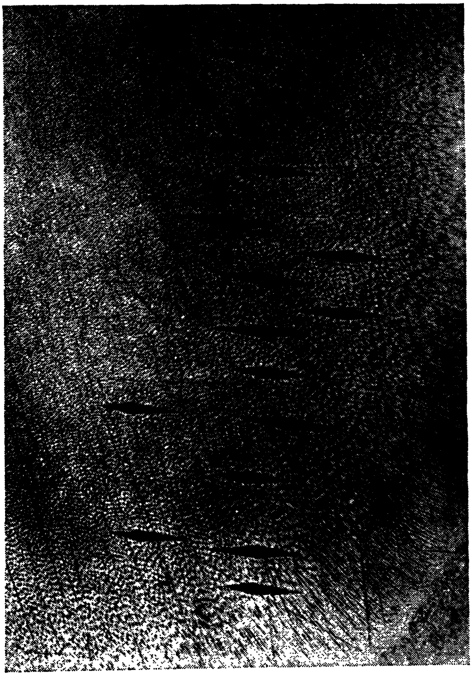


Figure 135. Impressions made on polished tooth structure. Load 300 grams.

(Courtesy Crosby F. Baker, Tufts College, Medford, Mass.)

from the change of length of the long diagonal, it is possible to determine the amount worn away during the brushing tests. The load applied is generally 300 grams. (See Fig. 135.)

Grinding Wheels

Indentation hardness tests are used to a limited extent in grading grinding wheels for hardness. The test is used to control the hardness of the bond rather than the hardness of the abrasive. The hardness of the abrasive particle could be determined with the Knoop Indenter (see Chapter XV.)

The Zeiss Abrasive Wheel Hardness Tester and the Grade-O-Meter (Abrasive Engineering Corp., Detroit, Michigan) are instruments used for hardness determination of grinding wheels, but these do not operate on the principle of applying a static load to a penetrator.

One of the principal uses of the indentation hardness test is the grading of stones used for superfinishing. These are generally vitrified bond stones and are tested on the Rockwell tester with a load of 60 kg and 1/8″ ball penetrator (H scale). The stones are supported on a flat anvil and the load is applied in the standard time. Vitrified bond stones of 320 and finer grit are tested in this manner.

Once a stone of proper hardness has been selected, stones graded according to the above will operate satisfactorily on the same material provided cutting speed, lubricant, pressure and size of grit remain the same. In finishing material of different hardness, it may be necessary to use stones of different hardnesses. Likewise different types of material require wheels of different hardness values.

Finishing grinding wheels may be tested using the E or H scales. The method of obtaining the hardness on the Rockwell tester from recovery of indentation after removal of major load (described earlier in this chapter) may be of great value especially with wheels which have been loaded, as for example, with paraffin.

Conclusion

The volume of work being down on non-metallic hardness testing by equipment designed for metal testing is very extensive; no attempt has been made to cover it in great detail. Sufficient has been given, however, to show the reader what may be accomplished along this line.

Prof. S. R. Williams of Amherst has pointed out that if hardness is a physical property, it must be universal for all solids and we must think of hardness in connection with solids other than metals. The development of the Knoop indenter at the National Bureau of Standards has probably done more to stimulate research in this field than any other one thing. To the physicist this is gratifying; and to the testing engineer it should prove valuable.

References

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Chapter XVII

Conclusion

From the description of the hardness testing equipment which has been given, and from the discussion of the various problems relating to the use of the equipment, an idea may be gained of the importance of the hardness test in industry. The use of the test has grown by leaps and bounds, and during World War II it was probably the most frequently used test in the metal-working industry. It is, of course, impossible to know accurately the extent of the use of the test, but during the high production days of the last war it is safe to assume that over 50,000,000 hardness determinations a day were made in this country. Since the end of the war, the hardness test has played an important part in the reconversion program, and because of the widespread use of the test during the war in organizations which never previously relied on hardness control the test is growing in importance and popularity. This is especially true in the small shop.

The great use of the hardness tester emphasizes the need of equipment that is properly designed, rugged and has lasting precision. Fortunately, such equipment is available. Modern hardness testing equipment is sensitive, accurate and remains in calibration for long periods. It is well adapted for production testing.

The lack of any absolute standard of hardness greatly handicaps the manufacturer of hardness testing equipment. In the past this drawback has been offset by careful standardization work in the laboratories of the more prominent manufacturers. Such work must of necessity continue, and these organizations have the necessary facilities for carrying on such work. Most important is the necessity of having available a large supply of newly built and properly calibrated instruments.

The great need is for more uniform material for use as standards for reference guides which are commonly known as "test blocks." The standardizing laboratories may have the proper information but it is necessary to get this to the user of the tester. This can be accomplished only by utilizing material of uniform hardness for test blocks. Materials are necessary which do not change in hardness with time, in which hundreds of tests may be made without change in hardness, which are not expensive and are easy to produce. There is great need for research along this line and it is suggested that the activities of technical societies and scientific bureaus be directed to this field. Such materials, if developed, will enable the manufacturer to control the standards of hardness to a much closer degree.

Methods of preparing surfaces so that the hardness is not superficially changed is another field which requires more study.

It must be kept in mind that the ease and simplicity of making the test may give a false impression that reliable results are invariably obtained. This is not so. Reliable tests are obtained only with proper care and a knowledge of all the factors which can produce errors.

With reference to the future of hardness testing, it may be in order to predict what is required. There is need for a fast, reliable hardness tester for use in production testing. The present high wage rate of labor increases the need for a machine which will double or triple the number of tests made with equipment currently available. The application of electronic controls to the hardness tester may make this possible. It has been tried in the past but the results were not too successful.

Microhardness testing is in its infancy and no prediction may be made as to what will be learned through this new development in the next few years. It should be helpful in solving many perplexing problems; as for example, the relation between hardness and machinability, the effect of various surface finishes, such as grinding, polishing, plating, and other processes. There is need for standardization in the methods of preparing surfaces. The American Society for Testing Materials is now working on this problem.

Heavy load testing needs some study. There is a tremendous difference between the size of impression made with the Rockwell tester or the 136° diamond pyramid test as compared to the Brinell impression. Probably many metallurgical problems could be solved with a hardness indentation somewhere between the two. There would be advantages to such a test.

It is hoped that this textbook will serve to give a better understanding of indentation hardness testing and the many problems relating thereto, and that it will stimulate research in indentation hardness testing. It is also hoped that it will convey the idea that there is more in hardness testing than the mere application of a load to a ball, cone or pyramid.

APPENDIX

Section I

Tables of Hardness Numbers

BRINELL HARDNESS NUMBERS

Diameter of Ball 10 Millimeters
Impression Diameters to 0.05 MM

	BRINELL HARDNESS NUMBERS					
Dia. of Inden-tation	500 KGM Load	1000 KGM Load	1500 KGM Load	2000 KGM Load	2500 KGM Load	3000 KGM Load
2.00	158	316	473	632	788	945
2.05	150	300	450	600	750	899
2.10	143	286	428	572	714	856
2.15	136	272	409	544	681	817
2.20	130	260	390	520	650	780
2.25	124	248	373	496	621	745
2.30	119	238	356	476	593	712
2.35	114	228	341	456	568	682
2.40	109	218	327	436	545	653
2.45	104	208	314	416	522	627
2.50	100	200	301	400	500	601
2.55	96.3	193	289	385	482	578
2.60	92.6	185	278	370	462	555
2.65	89.0	178	267	356	445	534
2.70	85.7	171	257	343	429	514
2.75	82.6	165	248	330	413	495
2.80	79.6	159	239	318	398	477
2.85	76.8	154	231	307	384	461
2.90	74.1	148	222	296	371	444
2.95	71.5	143	215	286	358	429
3.00	69.1	138	208	276	346	415
3.50	66.8	134	201	267	334	401
3.10	64.6	129	194	258	324	388
3.15	62.5	125	188	250	313	375
3.20	60.5	121	182	242	303	363
3.25	58.6	117	176	234	293	352
3.30	56.8	114	171	227	284	341
3.35	55.1	110	166	220	276	331
3.40	53.4	107	161	214	267	321
3.45	51.8	104	156	207	259	311

	BRINELL HARDNESS NUMBERS					
Dia. of Inden-tation	500 KGM Load	1000 KGM Load	1500 KGM Load	2000 KGM Load	2500 KGM Load	3000 KGM Load
3.50	50.3	101	151	201	252	302
3.55	48.9	97.8	147	196	244	293
3.60	47.5	95.0	143	190	238	285
3.65	46.1	92.2	139	184	231	277
3.70	44.9	89.8	135	180	225	269
3.75	43.6	87.2	131	174	218	262
3.80	42.4	84.8	128	170	212	255
3.85	41.3	82.6	124	165	207	248
3.90	40.2	80.4	121	161	201	241
3.95	39.1	78.2	118	156	196	235
4.00	38.1	76.2	115	152	191	229
4.05	37.1	74.2	112	148	186	223
4.10	36.2	72.4	109	145	181	217
4.15	35.3	70.6	106	141	177	212
4.20	34.4	68.8	104	138	172	207
4.25	33.6	67.2	101	134	167	201
4.30	32.8	65.6	98.5	131	164	197
4.35	32.0	64.0	96.0	128	160	192
4.40	31.2	62.4	93.5	125	156	187
4.45	30.5	61.0	91.5	122	153	183
4.50	29.8	59.6	89.5	119	149	179
4.55	29.1	58.2	87.0	116	145	174
4.60	28.4	56.8	85.0	114	142	170
4.65	27.8	55.6	83.5	111	139	167
4.70	27.1	54.2	81.5	108	136	163
4.75	26.5	53.0	79.5	106	133	159
4.80	25.9	51.8	78.0	104	130	156
4.85	25.4	50.8	76.0	102	127	152
4.90	24.8	49.6	74.5	99.2	124	149
4.95	24.3	48.6	73.0	97.2	122	146

	BRINELL HARDNESS NUMBERS					
Dia. of Inden-tation	500 KGM Load	1000 KGM Load	1500 KGM Load	2000 KGM Load	2500 KGM Load	3000 KGM Load
5.00	23.8	47.6	71.5	95.2	119	143
5.05	23.3	46.6	70.0	93.2	117	140
5.10	22.8	45.6	68.5	91.2	114	137
5.15	22.3	44.6	67.0	89.2	112	134
5.20	21.8	43.6	65.5	87.2	109	131
5.25	21.4	42.8	64.0	85.6	107	128
5.30	20.9	41.8	63.0	83.6	105	126
5.35	20.5	41.0	61.5	82.0	103	123
5.40	20.1	40.2	60.5	80.4	101	121
5.45	19.7	39.4	59.0	78.8	98.5	118
5.50	19.3	38.6	58.0	77.2	96.5	116
5.55	18.9	37.8	57.0	75.6	95.0	114
5.60	18.6	37.2	55.5	74.4	92.5	111
5.65	18.2	36.4	54.5	72.8	90.8	109
5.70	17.8	35.6	53.5	71.2	89.2	107
5.75	17.5	35.0	52.5	70.0	87.5	105
5.80	17.2	34.4	51.5	68.8	85.8	103
5.85	16.8	33.6	50.5	67.2	84.2	101
5.90	16.5	33.0	49.6	66.0	82.5	99.2
5.95	16.2	32.4	48.7	64.8	81.2	97.3
6.00	15.9	31.8	47.8	63.6	79.5	95.5
6.05	15.6	31.2	46.9	62.4	78.0	93.7
6.10	15.3	30.6	46.0	61.2	76.7	92.0
6.15	15.1	30.2	45.2	60.4	75.3	90.3
6.20	14.8	29.6	44.4	59.2	73.8	88.7
6.25	14.5	29.0	43.6	58.0	72.6	87.1
6.30	14.2	28.4	42.8	56.8	71.3	85.5
6.35	14.0	28.0	42.0	56.0	70.0	84.0
6.40	13.7	27.4	41.3	54.8	68.8	82.5
6.45	13.5	27.0	40.5	54.0	67.5	81.0

136° DIAMOND PYRAMID HARDNESS NUMBERS

Table for 1 Kg Load

This table is based on tests made with a load of 1 kilogram (1000 grams) and for tests so made with 1 kg it is only necessary to determine the length of the impression in millimeters by measuring both diagonals of the impression and taking the average of the two readings, then refer to the table. Against the length in millimeters is shown the 136° Diamond Pyramid Hardness Number (D.P.H.); no further computation is necessary.

If the test has been made with any other load than 1 kg, determine the length of impression as explained above, read the D.P.H. from the table for 1 kg then multiply this figure by the load used in kilograms.

If the test has been made with a load of less than 1 kg, then the load must be expressed as the decimal part of a kilogram and the D.P.H. multiplied by the figure so obtained.

(Courtesy Wilson Mechanical Instrument Co., New York, N. Y.)

Diagonal of Impression mm	.0000	.0001	.0002	.0003	.0004	.0005	.0006	.0007	.0008	.0009
.005	74174	71294	68578	66015	63592	61301	59131	57075	55124	53271
.006	51510	49835	48240	46721	45272	43890	42570	41309	40103	38949
.007	37844	36786	35771	34798	33863	32966	32104	31276	30479	29712
.008	28974	28263	27578	26918	26281	25666	25072	24499	23946	23411
.009	22893	22393	21909	21440	20986	20547	20121	19708	19308	18920
.010	18544	18178	17824	17479	17145	16820	16504	16197	15898	15608
.011	15325	15050	14783	14522	14269	14022	13781	13546	13318	13095
.012	12878	12666	12459	12257	12060	11868	11680	11497	11318	11143
.013	10972	10806	10643	10483	10327	10175	10026	9880	9737	9598
.014	9461	9327	9196	9068	8943	8820	8699	8581	8466	8353
.015	8242	8133	8026	7922	7819	7718	7620	7523	7428	7335
.016	7244	7154	7066	6979	6895	6811	6729	6649	6570	6493
.017	6416	6342	6268	6196	6125	6055	5986	5919	5853	5788
.018	5723	5660	5598	5537	5477	5418	5360	5303	5247	5191
.019	5137	5083	5030	4978	4927	4877	4827	4778	4730	4683
.020	4636	4590	4545	4500	4456	4413	4370	4328	4286	4245
.021	4205	4165	4126	4087	4049	4012	3974	3938	3902	3866
.022	3831	3797	3763	3729	3696	3663	3631	3599	3567	3536
.023	3505	3475	3445	3416	3387	3358	3329	3301	3274	3246
.024	3219	3193	3166	3140	3115	3089	3064	3040	3015	2991
.025	2967	2943	2920	2897	2874	2852	2830	2808	2786	2764
.026	2743	2722	2701	2681	2660	2641	2621	2601	2582	2563
.027	2544	2525	2506	2488	2470	2452	2434	2417	2399	2382
.028	2365	2348	2332	2315	2299	2283	2267	2251	2236	2220
.029	2205	2190	2175	2160	2145	2131	2116	2102	2088	2074
.030	2060	2047	2033	2020	2006	1993	1980	1968	1955	1942
.031	1930	1917	1905	1893	1881	1869	1857	1845	1834	1822
.032	1811	1800	1788	1777	1766	1756	1745	1734	1724	1713
.033	1703	1692	1682	1672	1662	1652	1642	1633	1623	1614
.034	1604	1595	1585	1576	1567	1558	1549	1540	1531	1522
.035	1514	1505	1497	1488	1480	1471	1463	1455	1447	1439
.036	1431	1423	1415	1407	1400	1392	1384	1377	1369	1362
.037	1354	1347	1340	1333	1326	1319	1312	1304	1298	1291
.038	1284	1278	1271	1264	1258	1251	1245	1238	1232	1225
.039	1219	1213	1207	1201	1194	1188	1182	1177	1171	1165
.040	1159	1153	1148	1142	1136	1130	1125	1120	1114	1108
.041	1103	1098	1092	1087	1082	1077	1072	1066	1061	1056
.042	1051	1046	1041	1036	1032	1027	1022	1017	1012	1008
.043	1003	998	994	989	984	980	976	971	967	962
.044	958	954	949	945	941	936	932	928	924	920
.045	916	912	908	904	900	896	892	888	884	880
.046	876	873	869	865	861	858	854	850	847	843
.047	840	836	832	829	825	822	818	815	812	808
.048	805	802	798	795	792	788	785	782	779	776
.049	772	769	766	763	760	757	754	751	748	745

136° Diamond Pyramid Hardness Numbers (*continued*)

Diagonal of Impression mm	.0000	.0001	.0002	.0003	.0004	.0005	.0006	.0007	.0008	.0009
.050	742	739	736	733	730	727	724	721	719	716
.051	713	710	707	705	702	699	696	694	691	688
.052	686	683	680	678	675	673	670	668	665	663
.053	660	658	655	653	650	648	646	643	641	638
.054	636	634	631	629	627	624	622	620	618	615
.055	613	611	609	606	604	602	600	598	596	593
.056	591	589	587	585	583	581	579	577	575	573
.057	571	569	567	565	563	561	559	557	555	553
.058	551	549	548	546	544	542	540	538	536	534
.059	533	531	529	527	526	524	522	520	519	517
.060	515	513	512	510	508	507	505	503	502	500
.061	498	497	495	494	492	490	489	487	486	484
.062	482	481	479	478	476	475	473	472	470	469
.063	467	466	464	463	461	460	458	457	456	454
.064	453	451	450	448	447	446	444	443	442	440
.065	439	438	436	435	434	432	431	430	428	427
.066	426	424	423	422	421	419	418	417	416	414
.067	413	412	411	409	408	407	406	405	403	402
.068	401	400	399	398	396	395	394	393	392	391
.069	390	388	387	386	385	384	383	383	381	380
.070	378	377	376	375	374	373	372	371	370	369
.071	368	367	366	365	364	363	362	361	360	359
.072	358	357	356	355	354	353	352	351	350	349
.073	348	347	346	345	344	343	342	341	340	340
.074	339	338	337	336	335	334	333	332	331	331
.075	330	329	328	327	326	325	324	324	323	322
.076	321	320	319	318	318	317	316	315	314	314
.077	313	312	311	310	309	309	308	307	307	306
.078	305	304	303	303	302	301	300	299	299	298
.079	297	296	296	295	294	293	293	292	291	291
.080	290	289	288	288	287	287	286	285	284	283
.081	283	282	281	280	280	279	278	278	277	277
.082	276	275	274	274	273	273	272	271	270	270
.083	269	268	268	267	267	266	265	265	264	263
.084	263	262	262	261	260	260	259	258	258	257
.085	257	256	256	255	254	254	253	253	252	251
.086	251	250	250	249	248	248	247	247	246	246
.087	245	244	244	243	243	242	242	241	241	240
.088	240	239	238	238	237	237	236	236	235	235
.089	234	234	233	233	232	232	231	230	230	229
.090	229	228	228	227	227	226	226	225	225	224
.091	224	223	223	223	222	222	221	221	220	220
.092	219	219	218	218	217	217	216	216	215	215
.093	214	214	214	213	213	212	212	211	211	210
.094	210	209	209	208	208	208	207	207	206	206
.095	205	205	205	204	204	203	203	202	202	202
.096	201	201	200	200	200	199	199	198	198	198
.097	197	197	196	196	196	195	195	194	194	194
.098	193	193	192	192	192	191	191	190	190	190
.099	189	189	188	188	188	187	187	187	186	186
.100	185	185	185	184	184	184	183	183	182	182
.101	182	181	181	181	180	180	180	179	179	179
.102	178	178	178	177	177	176	176	176	176	175
.103	175	174	174	174	173	173	173	172	172	172
.104	171	171	171	170	170	170	170	169	169	168
.105	168	168	168	167	167	167	166	166	166	165
.106	165	165	164	164	164	164	163	163	163	162
.107	162	162	161	161	161	160	160	160	160	159
.108	159	159	158	158	158	158	157	157	157	156
.109	156	156	156	155	155	155	154	154	154	154

136° Diamond Pyramid Hardness Numbers (*continued*)

Diagonal of Impression mm	.0000	.0001	.0002	.0003	.0004	.0005	.0006	.0007	.0008	.0009
.110	153	153	153	152	152	152	152	151.3	151.1	150.8
.111	150.5	150.2	149.9	149.7	149.4	149.2	148.9	148.6	148.4	148.1
.112	147.8	147.6	147.3	147.0	146.8	146.5	146.3	146.0	145.7	145.5
.113	145.2	144.9	144.7	144.5	144.2	143.9	143.7	143.5	143.2	142.9
.114	142.7	142.4	142.2	141.9	141.7	141.4	141.2	140.9	140.7	140.5
.115	140.2	139.9	139.7	139.5	139.3	139.0	138.8	138.5	138.3	138.1
.116	137.8	137.6	137.3	137.1	136.9	136.6	136.4	136.2	135.9	135.7
.117	135.4	135.2	135.0	134.8	134.5	134.3	134.1	133.9	133.7	133.4
.118	133.2	132.9	132.7	132.5	132.3	132.1	131.9	131.6	131.4	131.2
.119	131.0	130.7	130.5	130.3	130.1	129.9	129.6	129.4	129.2	129.0
.120	128.8	128.6	128.4	128.1	127.9	127.7	127.5	127.3	127.1	126.9
.121	126.7	126.4	126.2	126.0	125.8	125.6	125.4	125.2	125.0	124.8
.122	124.6	124.4	124.2	124.0	123.8	123.6	123.4	123.1	123.0	122.8
.123	122.6	122.4	122.2	121.9	121.8	121.6	121.4	121.2	121.0	120.8
.124	120.6	120.4	120.2	120.0	119.8	119.6	119.4	119.2	119.1	118.9
.125	118.7	118.5	118.3	118.1	117.9	117.7	117.5	117.3	117.1	116.9
.126	116.8	116.6	116.4	116.2	116.1	115.9	115.7	115.5	115.4	115.2
.127	115.0	114.8	114.6	114.4	114.2	114.0	113.9	113.7	113.5	113.3
.128	113.2	113.0	112.8	112.6	112.5	112.3	112.1	111.9	111.8	111.6
.129	111.4	111.2	111.1	110.9	110.7	110.6	110.4	110.2	110.1	109.9
.130	109.7	109.5	109.4	109.2	109.1	108.9	108.7	108.5	108.4	108.2
.131	108.0	107.9	107.7	107.5	107.4	107.2	107.0	106.8	106.6	106.5
.132	106.4	106.2	106.1	105.9	105.8	105.6	105.5	105.3	105.1	104.9
.133	104.8	104.6	104.5	104.4	104.2	104.0	103.9	103.7	103.6	103.4
.134	103.3	103.1	102.9	102.8	102.7	102.5	102.4	102.2	102.1	101.9
.135	101.8	101.6	101.5	101.3	101.2	101.0	100.9	100.7	100.6	100.4
.136	100.3	100.1	100.0	99.8	99.7	99.5	99.4	99.2	99.1	98.9
.137	98.8	98.7	98.5	98.4	98.2	98.1	97.9	97.8	97.7	97.5
.138	97.4	97.2	97.1	97.0	96.8	96.7	96.5	96.4	96.3	96.1
.139	96.0	95.8	95.7	95.6	95.4	95.3	95.2	95.0	94.9	94.7
.140	94.6	94.5	94.3	94.2	94.1	93.9	93.8	93.7	93.5	93.4
.141	93.3	93.1	93.0	92.9	92.7	92.6	92.5	92.4	92.2	92.1
.142	92.0	91.8	91.7	91.6	91.5	91.3	91.2	91.1	90.9	90.8
.143	90.7	90.6	90.4	90.3	90.2	90.1	89.9	89.8	89.7	89.6
.144	89.4	89.3	89.2	89.1	88.9	88.8	88.7	88.6	88.4	88.3
.145	88.2	88.1	88.0	87.8	87.7	87.6	87.5	87.4	87.2	87.1
.146	87.0	86.9	86.8	86.6	86.5	86.4	86.3	86.2	86.0	85.9
.147	85.8	85.7	85.6	85.5	85.4	85.2	85.1	85.0	84.9	84.8
.148	84.7	84.5	84.4	84.3	84.2	84.1	84.0	83.9	83.8	83.6
.149	83.5	83.4	83.3	83.2	83.1	83.0	82.9	82.7	82.6	82.5
.150	82.4	82.3	82.2	82.1	82.0	81.9	81.8	81.7	81.5	81.4
.151	81.3	81.2	81.1	81.0	80.9	80.8	80.7	80.6	80.5	80.4
.152	80.3	80.2	80.1	79.9	79.8	79.7	79.6	79.5	79.4	79.3
.153	79.2	79.1	79.0	78.9	78.8	78.7	78.6	78.5	78.4	78.3
.154	78.2	78.1	78.0	77.9	77.8	77.7	77.6	77.5	77.4	77.3
.155	77.2	77.1	77.0	76.9	76.8	76.7	76.6	76.5	76.4	76.3
.156	76.2	76.1	76.0	75.9	75.8	75.7	75.6	75.5	75.4	75.3
.157	75.2	75.1	75.0	74.9	74.9	74.8	74.7	74.6	74.5	74.4
.158	74.3	74.2	74.1	74.0	73.9	73.8	73.7	73.6	73.5	73.4
.159	73.4	73.3	73.2	73.1	73.0	72.9	72.8	72.7	72.6	72.5
.160	72.4	72.3	72.3	72.2	72.1	72.0	71.9	71.8	71.7	71.6
.161	71.5	71.5	71.4	71.3	71.2	71.1	71.0	70.9	70.8	70.7
.162	70.7	70.6	70.5	70.4	70.3	70.2	70.1	70.1	70.0	69.9
.163	69.8	69.7	69.6	69.5	69.5	69.4	69.3	69.2	69.1	69.0
.164	69.0	68.9	68.8	68.7	68.6	68.5	68.4	68.4	68.3	68.2
.165	68.1	68.0	68.0	67.9	67.8	67.7	67.6	67.5	67.5	67.4
.166	67.3	67.2	67.1	67.1	67.0	66.9	66.8	66.7	66.6	66.6
.167	66.5	66.4	66.3	66.3	66.2	66.1	66.0	65.9	65.9	65.8
.168	65.7	65.6	65.6	65.5	65.4	65.3	65.2	65.2	65.1	65.0
.169	64.9	64.9	64.8	64.7	64.6	64.5	64.5	64.4	64.3	64.2

136° Diamond Pyramid Hardness Numbers (*continued*)

Diagonal of Impression mm	.0000	.0001	.0002	.0003	.0004	.0005	.0006	.0007	.0008	.0009
.170	64.2	64.1	64.0	63.9	63.9	63.8	63.7	63.6	63.6	63.5
.171	63.4	63.3	63.3	63.2	63.1	63.1	63.0	62.9	62.8	62.8
.172	62.7	62.6	62.5	62.5	62.4	62.3	62.2	62.2	62.1	62.0
.173	62.0	61.9	61.8	61.7	61.7	61.6	61.5	61.5	61.4	61.3
.174	61.3	61.2	61.1	61.0	61.0	60.9	60.8	60.8	60.7	60.6
.175	60.6	60.5	60.4	60.3	60.3	60.2	60.1	60.1	60.0	59.9
.176	59.9	59.8	59.7	59.7	59.6	59.5	59.5	59.4	59.3	59.3
.177	59.2	59.1	59.1	59.0	58.9	58.9	58.8	58.7	58.7	58.6
.178	58.5	58.5	58.4	58.3	58.3	58.2	58.1	58.1	58.0	58.0
.179	57.9	57.8	57.7	57.7	57.6	57.6	57.5	57.4	57.4	57.3
.180	57.2	57.2	57.1	57.0	57.0	56.9	56.8	56.8	56.7	56.7
.181	56.6	56.5	56.5	56.4	56.4	56.3	56.2	56.2	56.1	56.0
.182	56.0	55.9	55.9	55.8	55.7	55.7	55.6	55.6	55.5	55.4
.183	55.4	55.3	55.3	55.2	55.1	55.1	55.0	55.0	54.9	54.8
.184	54.8	54.7	54.7	54.6	54.5	54.5	54.4	54.4	54.3	54.2
.185	54.2	54.1	54.1	54.0	54.0	53.9	53.8	53.8	53.7	53.7
.186	53.6	53.5	53.5	53.4	53.4	53.3	53.3	53.2	53.1	53.1
.187	53.0	53.0	52.9	52.9	52.8	52.7	52.7	52.6	52.6	52.5
.188	52.5	52.4	52.4	52.3	52.2	52.2	52.1	52.1	52.0	52.0
.189	51.9	51.9	51.8	51.7	51.7	51.6	51.6	51.5	51.5	51.4
.190	51.4	51.3	51.3	51.2	51.2	51.1	51.0	51.0	50.9	50.9
.191	50.8	50.8	50.7	50.7	50.6	50.6	50.5	50.5	50.4	50.4
.192	50.3	50.3	50.2	50.1	50.1	50.0	50.0	49.9	49.9	49.8
.193	49.8	49.7	49.7	49.6	49.6	49.5	49.5	49.4	49.4	49.3
.194	49.3	49.2	49.2	49.1	49.1	49.0	49.0	48.9	48.9	48.8
.195	48.8	48.7	48.7	48.6	48.6	48.5	48.5	48.4	48.4	48.3
.196	48.3	48.2	48.2	48.1	48.1	48.0	48.0	47.9	47.9	47.8
.197	47.8	47.7	47.7	47.6	47.6	47.5	47.5	47.4	47.4	47.3
.198	47.3	47.3	47.2	47.2	47.1	47.1	47.0	47.0	46.9	46.9
.199	46.8	46.8	46.7	46.7	46.6	46.6	46.5	46.5	46.5	46.4
.200	46.4									

KNOOP Hardness Numbers

The KNOOP Indenter is pyramidal in form, giving a diamond-shaped (rhomb) indentation of which the diagonals have an approximate relation of 7 to 1. The longitudinal angle is 172° 30′ and the transverse angle is 130° 0′. The "TUKON" TESTER applies loads upward from 25 grams.

Elastic recovery of indentations with the KNOOP Indenter takes place chiefly in a transverse rather than in a longitudinal direction, and consequently from the measured length of the long diagonal and the constants of the indenter, dimensions of an indentation closely related to the unrecovered length are obtained. The result of test is expressed as the KNOOP Hardness Number which relates the applied load in kilograms to the unrecovered (approximate) 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 elastic recovery of the material being investigated may be studied.

The KNOOP Hardness Number is expressed by the formula

$$I = \frac{L}{Ap} = \frac{L}{l^2\,Cp}.$$

I = KNOOP Hardness Number
L = Load (in kilograms) applied to indenter
Ap = Unrecovered projected area of indentation (in square mm)
l = Measured length of long diagonal of the indentation (in mm)
Cp = Constant relating l to the projected area. For a perfect indenter of 170° 30′ longitudinal angle and 130° 0′ transverse angle, Cp equals 7.028×10^{-2}

The indentation number corresponding to a measured length, l, for a load of 1.0 kg may be determined from the table. To obtain the KNOOP Hardness Number for any other load, multiply the hardness of 1.0 kg load in the table by the applied load in kg.

> Example: A piece of material tested on the "TUKON" TESTER under a load of 500 grams (.5 kg) and showing a length of .100 mm (100μ) when the long diagonal is measured under a microscope, would give a KNOOP Hardness Number for this length of 1423 according to the table. As the load applied is only 500 grams (.5 kg) and the table is computed for 1000 grams (1.0 kg) this value of 1423 must be multiplied by .5 to give the correct value of 711.5 for the KNOOP Hardness Number under a load of 500 grams (.5 kg).

The table is computed for a theoretically perfect indenter of 172° 30′ longitudinal angle and 130° 0′ transverse angle, and having a constant for projected area (Cp) of 7.028×10^{-1}. It can be used for determination of KNOOP Hardness Number with any indenter meeting the specifications of the National Bureau of Standards without appreciable error.

By measuring the width of the indentation, the hardness number based on the recovered indentation may be determined, thus giving data for a study of elastic recovery.

Knoop Hardness Numbers when load is 1.0 kg and indenter has included longitudinal angle of 172° 30′ and included transverse angle of 130° 0′.

Length of Indentation in mm	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009
.010	142,290	117,595	98,812	84,195	72,597	63,240	55,582	49,235	43,917	39,415
.020	35,572	32,265	29,399	26,898	24,703	22,766	21,049	19,518	18,149	16,919
.030	15,810	14,806	13,895	13,066	12,309	11,615	10,979	10,394	9,854	9,355
.040	8,893	8,465	8,066	7,695	7,350	7,027	6,724	6,441	6,176	5,926
.050	5,692	5,471	5,262	5,065	4,880	4,704	4,537	4,379	4,230	4,088
.060	3,952	3,824	3,702	3,585	3,474	3,368	3,267	3,170	3,077	2,989
.070	2,904	2,823	2,745	2,670	2,598	2,530	2,463	2,400	2,339	2,280
.080	2,223	2,169	2,116	2,065	2,017	1,969	1,924	1,880	1,837	1,796
.090	1,757	1,718	1,681	1,645	1,610	1,577	1,544	1,512	1,482	1,452
.100	1,423	1,395	1,368	1,341	1,316	1,291	1,266	1,243	1,220	1,198
.110	1,176	1,155	1,134	1,114	1,095	1,076	1,057	1,039	1,022	1,005
.120	988.1	971.9	956.0	940.5	925.4	910.7	896.3	882.2	868.5	855.1
.130	842.0	829.1	816.6	804.4	792.4	780.7	769.3	758.1	747.2	736.5
.140	726.0	715.7	705.7	695.8	686.2	676.8	667.5	658.5	649.6	640.9
.150	632.4	624.0	615.9	607.8	600.0	592.3	584.7	577.3	570.0	562.8
.160	555.8	548.9	542.2	535.5	529.0	522.6	516.4	510.2	504.1	498.2
.170	492.4	486.6	481.0	475.4	470.0	464.6	459.4	454.2	449.1	444.1
.180	439.2	434.3	429.6	424.9	420.3	415.7	411.3	406.9	402.6	398.3
.190	394.2	390.0	386.0	382.0	378.1	374.2	370.4	366.6	362.9	359.3
.200	355.7	352.2	348.7	345.3	341.9	338.6	335.3	332.1	328.9	325.7
.210	322.7	319.6	316.6	313.6	310.7	307.8	305.0	302.2	299.4	296.7
.220	294.0	291.3	288.7	286.1	283.6	281.1	278.6	276.1	273.7	271.3
.230	269.0	266.7	264.4	262.1	259.9	257.7	255.5	253.3	251.2	249.1
.240	247.0	245.0	243.0	241.0	239.0	237.1	235.1	233.2	231.4	229.5
.250	227.7	225.9	224.1	222.3	220.5	218.8	217.1	215.4	213.8	212.1
.260	210.5	208.9	207.3	205.7	204.2	202.6	201.1	199.6	198.1	196.6
.270	195.2	193.7	192.3	190.9	189.5	188.2	186.8	185.4	184.1	182.8
.280	181.5	180.2	178.9	177.7	176.4	175.2	174.0	172.7	171.5	170.4
.290	169.2	168.0	166.9	165.7	164.6	163.5	162.4	161.3	160.2	159.2
.300	158.1	157.1	156.0	155.0	154.0	153.0	152.0	151.0	150.0	149.0
.310	148.1	147.1	146.2	145.2	144.3	143.4	142.5	141.6	140.7	139.8
.320	139.0	138.1	137.2	136.4	135.5	134.7	133.9	133.1	132.3	131.5
.330	130.7	129.9	129.1	128.3	127.5	126.8	126.0	125.3	124.5	123.8
.340	123.1	122.4	121.7	120.9	120.2	119.5	118.9	118.2	117.5	116.8
.350	116.2	115.5	114.8	114.2	113.5	112.9	112.3	111.6	111.0	110.4
.360	109.8	109.2	108.6	108.0	107.4	106.8	106.2	105.6	105.1	104.5
.370	103.9	103.4	102.8	102.3	101.7	101.2	100.6	100.1	99.58	99.06
.380	98.54	98.02	97.51	97.00	96.50	96.00	95.50	95.01	94.52	94.03
.390	93.55	93.07	92.60	92.13	91.66	91.20	90.74	90.28	89.83	89.38
.400	88.93	88.49	88.05	87.61	87.18	86.75	86.32	85.90	85.48	85.06
.410	84.65	84.23	83.83	83.42	83.02	82.62	82.22	81.83	81.44	81.05
.420	80.66	80.28	79.90	79.52	79.15	78.78	78.41	78.04	77.68	77.31
.430	76.95	76.60	76.24	75.89	75.54	75.20	74.85	74.51	74.17	73.83
.440	73.50	73.16	72.83	72.50	72.18	71.85	71.53	71.21	70.90	70.58
.450	70.27	69.96	69.65	69.34	69.03	68.73	68.43	68.13	67.83	67.54
.460	67.24	66.95	66.66	66.38	66.09	65.81	65.52	65.24	64.97	64.69
.470	64.41	64.14	63.87	63.60	63.33	63.06	62.80	62.54	62.28	62.02
.480	61.76	61.50	61.25	60.99	60.74	60.49	60.24	60.00	59.75	59.51
.490	59.26	59.02	58.78	58.54	58.31	58.07	57.84	57.61	57.37	57.14
.500	56.92	56.69	56.46	56.24	56.02	55.79	55.57	55.36	55.14	54.92
.510	54.71	54.49	54.28	54.07	53.86	53.65	53.44	53.23	53.03	52.82

Knoop Hardness Numbers (*continued*)

Length of Indentation in mm	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009
.520	52.62	52.42	52.22	52.02	51.82	51.62	51.43	51.23	51.04	50.85
.530	50.65	50.46	50.27	50.09	49.90	49.71	49.53	49.34	49.16	48.98
.540	48.80	48.62	48.44	48.26	48.08	47.90	47.73	47.56	47.38	47.21
.550	47.04	46.87	46.70	46.53	46.36	46.19	46.03	45.86	45.70	45.54
.560	45.37	45.21	45.05	44.89	44.73	44.57	44.42	44.26	44.10	43.95
.570	43.79	43.64	43.49	43.34	43.19	43.04	42.89	42.74	42.59	42.44
.580	42.30	42.15	42.01	41.86	41.72	41.58	41.44	41.29	41.15	41.01
.590	40.88	40.74	40.60	40.46	40.33	40.19	40.06	39.92	39.79	39.66
.600	39.52	39.39	39.26	39.13	39.00	38.87	38.75	38.62	38.49	38.37
.610	38.24	38.11	37.99	37.87	37.74	37.62	37.50	37.38	37.26	37.14
.620	37.02	36.90	36.78	36.66	36.54	36.43	36.31	36.19	36.08	35.96
.630	35.85	35.74	35.62	35.51	35.40	35.29	35.18	35.07	34.96	34.85
.640	34.74	34.63	34.52	34.42	34.31	34.20	34.10	33.99	33.89	33.78
.650	33.68	33.57	33.47	33.37	33.27	33.17	33.06	32.96	32.86	32.76
.660	32.67	32.57	32.47	32.37	32.27	32.18	32.08	31.98	31.89	31.79
.670	31.70	31.60	31.51	31.42	31.32	31.23	31.14	31.05	30.95	30.86
.680	30.77	30.68	30.59	30.50	30.41	30.32	30.24	30.15	30.06	29.97
.690	29.89	29.80	29.71	29.63	29.54	29.46	29.37	29.29	29.21	29.12
.700	29.04	28.96	28.87	28.79	28.71	28.63	28.55	28.47	28.39	28.31
.710	28.23	28.15	28.07	27.99	27.91	27.83	27.76	27.68	27.60	27.52
.720	27.45	27.37	27.30	27.22	27.15	27.07	27.00	26.92	26.85	26.77
.730	26.70	26.63	26.56	26.48	26.41	26.34	26.27	26.20	26.13	26.05
.740	25.98	25.91	25.84	25.77	25.71	25.64	25.57	25.50	25.43	25.36
.750	25.30	25.23	25.16	25.09	25.03	24.96	24.90	24.83	24.76	24.70
.760	24.63	24.57	24.51	24.44	24.38	24.31	24.25	24.19	24.12	24.06
.770	24.00	23.94	23.87	23.81	23.75	23.69	23.63	23.57	23.51	23.45
.780	23.39	23.33	23.27	23.21	23.15	23.09	23.03	22.97	22.92	22.86
.790	22.80	22.74	22.68	22.63	22.57	22.51	22.46	22.40	22.34	22.29
.800	22.23	22.18	22.12	22.07	22.01	21.96	21.90	21.85	21.79	21.74
.810	21.69	21.63	21.58	21.53	21.47	21.42	21.37	21.32	21.27	21.21
.820	21.16	21.11	21.06	21.01	20.96	20.91	20.86	20.80	20.75	20.70
.830	20.65	20.60	20.56	20.51	20.46	20.41	20.36	20.31	20.26	20.21
.840	20.17	20.12	20.07	20.02	19.98	19.93	19.88	19.83	19.79	19.74
.850	19.69	19.65	19.60	19.56	19.51	19.46	19.42	19.37	19.33	19.28
.860	19.24	19.19	19.15	19.11	19.06	19.02	18.97	18.93	18.89	18.84
.870	18.80	18.76	18.71	18.67	18.63	18.58	18.54	18.50	18.46	18.42
.880	18.37	18.33	18.29	18.25	18.21	18.17	18.13	18.09	18.04	18.00
.890	17.96	17.92	17.88	17.84	17.80	17.76	17.72	17.68	17.64	17.61
.900	17.57	17.53	17.49	17.45	17.41	17.37	17.33	17.30	17.26	17.22
.910	17.18	17.14	17.11	17.07	17.03	17.00	16.96	16.92	16.88	16.85
.920	16.81	16.77	16.74	16.70	16.67	16.63	16.59	16.56	16.52	16.49
.930	16.45	16.42	16.38	16.35	16.31	16.28	16.24	16.21	16.17	16.14
.940	16.10	16.07	16.04	16.00	15.97	15.93	15.90	15.87	15.83	15.80
.950	15.77	15.73	15.70	15.67	15.63	15.60	15.57	15.54	15.50	15.47
.960	15.44	15.41	15.38	15.34	15.31	15.28	15.25	15.22	15.19	15.15
.970	15.12	15.09	15.06	15.03	15.00	14.97	14.94	14.91	14.88	14.85
.980	14.82	14.79	14.76	14.73	14.70	14.67	14.64	14.61	14.58	14.55
.990	14.52	14.49	14.46	14.43	14.40	14.37	14.34	14.31	14.29	14.26
1.000	14.23	14.20	14.17	14.14	14.12	14.09	14.06	14.03	14.00	13.98
1.010	13.95	13.92	13.89	13.87	13.84	13.81	13.78	13.76	13.73	13.70

Knoop Hardness Numbers (*continued*)

Length of Indentation in mm	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009
1.020	13.68	13.65	13.62	13.60	13.57	13.54	13.52	13.49	13.46	13.44
1.030	13.41	13.39	13.36	13.33	13.31	13.28	13.26	13.23	13.21	13.18
1.040	13.16	13.13	13.11	13.08	13.05	13.03	13.00	12.98	12.96	12.93
1.050	12.91	12.88	12.86	12.83	12.81	12.78	12.76	12.74	12.71	12.69
1.060	12.66	12.64	12.62	12.59	12.57	12.55	12.52	12.50	12.47	12.45
1.070	12.43	12.40	12.38	12.36	12.34	12.31	12.29	12.27	12.24	12.22
1.080	12.20	12.18	12.15	12.13	12.11	12.09	12.06	12.04	12.02	12.00
1.090	11.98	11.95	11.93	11.91	11.89	11.87	11.85	11.82	11.80	11.78
1.100	11.76	11.74	11.72	11.70	11.67	11.65	11.63	11.61	11.59	11.57
1.110	11.55	11.53	11.51	11.49	11.47	11.45	11.42	11.40	11.38	11.36
1.120	11.34	11.32	11.30	11.28	11.26	11.24	11.22	11.20	11.18	11.16
1.130	11.14	11.12	11.10	11.08	11.06	11.05	11.03	11.01	10.99	10.97
1.140	10.95	10.93	10.91	10.89	10.87	10.85	10.83	10.82	10.80	10.78
1.150	10.76	10.74	10.72	10.70	10.68	10.67	10.65	10.63	10.61	10.59
1.160	10.57	10.56	10.54	10.52	10.50	10.48	10.47	10.45	10.43	10.41
1.170	10.39	10.38	10.36	10.34	10.32	10.31	10.29	10.27	10.25	10.24
1.180	10.22	10.20	10.18	10.17	10.15	10.13	10.12	10.10	10.08	10.06
1.190	10.05	10.03	10.01	9.998	9.981	9.964	9.947	9.931	9.914	9.898
1.200	9.881	9.865	9.848	9.832	9.816	9.799	9.783	9.767	9.751	9.735
1.210	9.719	9.703	9.687	9.671	9.655	9.639	9.623	9.607	9.591	9.576
1.220	9.560	9.544	9.529	9.513	9.498	9.482	9.467	9.451	9.436	9.420
1.230	9.405	9.390	9.375	9.359	9.344	9.329	9.314	9.299	9.284	9.269
1.240	9.254	9.239	9.224	9.209	9.195	9.180	9.165	9.150	9.136	9.121
1.250	9.107	9.092	9.077	9.063	9.049	9.034	9.020	9.005	8.991	8.977
1.260	8.963	8.948	8.934	8.920	8.906	8.892	8.878	8.864	8.850	8.836
1.270	8.822	8.808	8.794	8.780	8.767	8.753	8.739	8.726	8.712	8.698
1.280	8.685	8.671	8.658	8.644	8.631	8.617	8.604	8.590	8.577	8.564
1.290	8.551	8.537	8.524	8.511	8.498	8.485	8.472	8.458	8.445	8.432
1.300	8.420	8.407	8.394	8.381	8.368	8.355	8.342	8.330	8.317	8.304
1.310	8.291	8.279	8.266	8.254	8.241	8.229	8.216	8.204	8.191	8.179
1.320	8.166	8.154	8.142	8.129	8.117	8.105	8.093	8.080	8.068	8.056
1.330	8.044	8.032	8.020	8.008	7.996	7.984	7.972	7.960	7.948	7.936
1.340	7.924	7.913	7.901	7.889	7.877	7.866	7.854	7.842	7.831	7.819
1.350	7.807	7.796	7.784	7.773	7.761	7.750	7.738	7.727	7.716	7.704
1.360	7.693	7.682	7.670	7.659	7.648	7.637	7.626	7.614	7.603	7.592
1.370	7.581	7.570	7.559	7.548	7.537	7.526	7.515	7.504	7.493	7.482
1.380	7.472	7.461	7.450	7.439	7.428	7.418	7.407	7.396	7.386	7.375
1.390	7.365	7.354	7.343	7.333	7.322	7.312	7.301	7.291	7.280	7.270
1.400	7.260	7.249	7.239	7.229	7.218	7.208	7.198	7.188	7.177	7.167
1.410	7.157	7.147	7.137	7.127	7.117	7.107	7.097	7.087	7.077	7.067
1.420	7.057	7.047	7.037	7.027	7.017	7.007	6.997	6.988	6.978	6.968
1.430	6.958	6.949	6.939	6.929	6.920	6.910	6.900	6.891	6.881	6.872
1.440	6.862	6.852	6.843	6.833	6.824	6.815	6.805	6.796	6.786	6.777
1.450	6.768	6.758	6.749	6.740	6.730	6.721	6.712	6.703	6.694	6.684
1.460	6.675	6.666	6.657	6.648	6.639	6.630	6.621	6.612	6.603	6.594
1.470	6.585	6.576	6.567	6.558	6.549	6.540	6.531	6.522	6.514	6.505
1.480	6.496	6.487	6.479	6.470	6.461	6.452	6.444	6.435	6.426	6.418
1.490	6.409	6.401	6.392	6.383	6.375	6.366	6.358	6.349	6.341	6.332
1.500	6.324									

Section II

Hardness Conversion Tables

Wilson Chart 38: Approximate Relationships between Hardness Values Determined on Rockwell and Rockwell Superficial Hardness Testers and those of other Testers.

All so-called "conversion" tables of hardness scales, including those here published, are and must be based on the assumption that the metal tested is homogeneous to a depth several times as great as the depth of the indentation, because different loads and different shapes of penetrators would, in metal not homogeneous, penetrate—or at least meet the resistance of—metal of varying hardness, depending upon the depth of the indentation, hence, no definite hardness value would actually exist and no recorded hardness value would be valid to an extent that could be confirmed by another person unless shape of penetrator and actual load applied are both specified.

These fundamentally essential specifications as to both loads and penetrators are and always have been fully covered in the recording of readings obtained on "Rockwell" Hardness Testers by the use of alphabetical symbols.

Conversion tables dealing with hardness can be only approximate and never mathematically exact, for it must be understood that a penetration hardness test proceeds until the specimen tested supports the applied load. Yet it is a severely cold-worked metal that actually supports the penetrator, and different metals, different alloys, and different analyses of the same type of alloy, have different cold-working properties. Nevertheless, while a conversion table cannot be mathematically exact, it is of considerable value to be able to compare different hardness scales in a general way.

For unhardened steel, steel of soft temper, gray and malleable cast iron and most non-ferrous metal

B.	F.	G.	15-T **	30-T **	45-T **	E.	K.	A.	Brinell	Brinell	Tensile Strength
"ROCKWELL" HARDNESS TESTER B scale 1/16" Ball penetrator—100 kg Load	"ROCKWELL" HARDNESS TESTER F scale 1/16" Ball penetrator—60 kg Load	"ROCKWELL" HARDNESS TESTER G scale 1/16" Ball penetrator—150 kg Load	"ROCKWELL" SUPERFICIAL 15-T scale 1/16" Ball penetrator—15 kg Load	"ROCKWELL" SUPERFICIAL 30-T scale 1/16" Ball penetrator—30 kg Load	"ROCKWELL" SUPERFICIAL 45-T scale 1/16" Ball penetrator—45 kg Load	"ROCKWELL" HARDNESS TESTER E scale 1/8" Ball penetrator—100 kg Load	"ROCKWELL" HARDNESS TESTER K scale 1/8" Ball penetrator—150 kg Load	"ROCKWELL" HARDNESS TESTER A scale "BRALE" penetrator—60 kg Load	Brinell, Standard Type, 500 kg Load 10 mm Ball penetrator	Brinell, Standard Type, 3000 kg Load 10 mm Ball penetrator	Thousand lbs per sq in.
100		82.5	93.0	82.0	72.0			61.5	201	240	116
99		81.0	92.5	81.5	71.0			61.0	195	234	112
98		79.0		81.0	70.0			60.0	189	228	109
97		77.5	92.0	80.5	69.0			59.5	184	222	106
96		76.0		80.0	68.0			59.0	179	216	103
95		74.0	91.5	79.0	67.0			58.0	175	210	101
94		72.5		78.5	66.0			57.5	171	205	98
93		71.0	91.0	78.0	65.5			57.0	167	200	96
92		69.0	90.5	77.5	64.5		100	56.5	163	195	93
91		67.5		77.0	63.5		99.5	56.0	160	190	91
90		66.0	90.0	76.0	62.5		98.5	55.5	157	185	89
89		64.0	89.5	75.5	61.5		98.0	55.0	154	180	87

B.	F.	G.	15-T **	30-T **	45-T **	E.	H.	K.	A.	Brinell
"ROCKWELL" HARDNESS TESTER B scale 1/16" Ball penetrator—100 kg Load	"ROCKWELL" HARDNESS TESTER F scale 1/16" Ball penetrator—60 kg Load	"ROCKWELL" HARDNESS TESTER G scale 1/16" Ball penetrator—150 kg Load	"ROCKWELL" SUPERFICIAL 15-T scale 1/16" Ball penetrator—15 kg Load	"ROCKWELL" SUPERFICIAL 30-T scale 1/16" Ball penetrator—30 kg Load	"ROCKWELL" SUPERFICIAL 45-T scale 1/16" Ball penetrator—45 kg Load	"ROCKWELL" HARDNESS TESTER E scale 1/8" Ball penetrator—100 kg Load	"ROCKWELL" HARDNESS TESTER H scale 1/8" Ball penetrator—60 kg Load	"ROCKWELL" HARDNESS TESTER K scale 1/8" Ball penetrator—150 kg Load	"ROCKWELL" HARDNESS TESTER A scale "BRALE" penetrator—60 kg Load	Brinell, Standard Type, 500 kg Load 10 mm Ball penetrator
50	85.5	2.5	77.0	49.5	23.0	87.0		64.5	35.0	83
49	85.0	1.0	76.5	49.0	22.0	86.5		63.5		82
48	84.5			48.5	20.5	85.5		62.5	34.5	81
47	84.0		76.0	47.5	19.5	85.0		61.5	34.0	80
46	83.0		75.5	47.0	18.5	84.5		61.0	33.5	
45	82.5			46.0	17.5	84.0		60.0	33.0	79
44	82.0		75.0	45.5	16.5	83.5		59.0	32.5	78
43	81.5		74.5	45.0	15.5	82.5		58.0	32.0	77
42	81.0			44.0	14.5	82.0		57.5	31.5	76
41	80.5		74.0	43.5	13.5	81.5		56.5	31.0	75
40	79.5		73.5	43.0	12.5	81.0		55.5		
39	79.0			42.0	11.0	80.0		54.5	30.5	74

88		62.5		75.0	60.5		97.0	54.0	151	176	85
87		61.0	89.0	74.5	59.5		96.5	53.5	148	172	83
86		59.0	88.5	74.0	58.5		95.5	53.0	145	169	81
85		57.5		73.5	58.0		94.5	52.5	142	165	80
84		56.0	88.0	73.0	57.0		94.0	52.0	140	162	78
83		54.0	87.5	72.0	56.0		93.0	51.0	137	159	77
82		52.5		71.5	55.0		92.0	50.5	135	156	75
81		51.0	87.0	71.0	54.0		91.0	50.0	133	153	74
80		49.0	86.5	70.0	53.0		90.5	49.5	130	150	72
79		47.5		69.5	52.0		89.5	49.0	128	147	
78		46.0	86.0	69.0	51.0		88.5	48.5	126	144	
77		44.0	85.5	68.0	50.0		88.0	48.0	124	141	
76		42.5		67.5	49.0		87.0	47.0	122	139	
75	99.5	41.0	85.0	67.0	48.5		86.0	46.5	120	137	
74	99.0	39.0		66.0	47.5		85.0	46.0	118	135	
73	98.5	37.5	84.5	65.5	46.5		84.5	45.5	116	132	
72	98.0	36.0	84.0	65.0	45.5		83.5	45.0	114	130	
71	97.5	34.5		64.0	44.5	100	82.5	44.5	112	127	
70	97.0	32.5	83.5	63.5	43.5	99.5	81.5	44.0	110	125	
69	96.0	31.0	83.0	62.5	42.5	99.0	81.0	43.5	109	123	
68	95.5	29.5		62.0	41.5	98.0	80.0	43.0	107	121	
67	95.0	28.0	82.5	61.5	40.5	97.5	79.0	42.5	106	119	
66	94.5	26.5	82.0	60.5	39.5	97.0	78.0	42.0	104	117	
65	94.0	25.0		60.0	38.5	96.0	77.7		102	116	
64	93.5	23.5	81.5	59.5	37.5	95.5	76.5	41.5	101	114	
63	93.0	22.0	81.0	58.5	36.5	95.0	75.5	41.0	99	112	
62	92.0	20.5		58.0	35.5	94.5	74.5	40.5	98	110	
61	91.5	19.0	80.5	57.0	34.5	93.5	74.0	40.0	96	108	
60	91.0	17.5		56.5	33.5	93.0	73.0	39.5	95	107	
59	90.5	16.0	80.0	56.0	32.0	92.5	72.0	39.0	94	106	
58	90.0	14.5	79.5	55.0	31.0	92.0	71.0	38.5	92	104	
57	89.5	13.0		54.5	30.0	91.0	70.5	38.0	91	103	
56	89.0	11.5	79.0	54.0	29.0	90.5	69.5		90	101	
55	88.0	10.0	78.5	53.0	28.0	90.0	68.5	37.5	89	100	
54	87.5	8.5		52.5	27.0	89.5	68.0	37.0	87		
53	87.0	7.0	78.0	51.5	26.0	89.0	67.0	36.5	86		
52	86.5	5.5	77.5	51.0	25.0	88.0	66.0	36.0	85		
51	86.0	4.0		50.5	24.0	87.5	65.0	35.5	84		
50	85.5	2.5	77.0	49.5	23.0	87.0	64.5	35.0	83		

Even for steel, Tensile Strength relation to hardness is inexact, unless determined for specific material.

38	78.5		73.0	41.5	10.0	79.5		54.0	30.0	73
37	78.0		72.5	40.5	9.0	79.0		53.0	29.5	72
36	77.5			40.0	8.0	78.5	100	52.0	29.0	
35	77.0		72.0	39.5	7.0	78.0	99.5	51.5	28.5	71
34	76.5		71.5	38.5	6.0	77.0	99.0	50.5	28.0	70
33	75.5			38.0	5.0	76.5		49.5		69
32	75.0		71.0	37.5	4.0	76.0	98.5	48.5	27.5	
31	74.5			36.5	3.0	75.5	98.0	48.0	27.0	68
30	74.0		70.5	36.0	2.0	75.0		47.0	26.5	67
29	73.5		70.0	35.5	1.0	74.0	97.5	46.0	26.0	
28	73.0			34.5		73.5	97.0	45.0	25.5	66
27	72.5		69.5	34.0		73.0	96.5	44.5	25.0	
26	72.0		69.0	33.0		72.5		43.5	24.5	65
25	71.0			32.5		72.0	96.0	42.5		64
24	70.5		68.5	32.0		71.0	95.5	41.5	24.0	
23	70.0		68.0	31.0		70.5		41.0	23.5	63
22	69.5			30.5		70.0	95.0	40.0	23.0	
21	69.0		67.5	29.5		69.5	94.5	39.0	22.5	62
20	68.5			29.0		68.5		38.0	22.0	
19	68.0		67.0	28.5		68.0	94.0	37.5	21.5	61
18	67.0		66.5	27.5		67.5	93.5	36.5		
17	66.5			27.0		67.0	93.0	35.5	21.0	60
16	66.0		66.0	26.0		66.5		35.0	20.5	
15	65.5		65.5	25.5		65.5	92.5	34.0	20.0	59
14	65.0			25.0		65.0	92.0	33.0		
13	64.5		65.0	24.0		64.5		32.0		58
12	64.0		64.5	23.5		64.0	91.5	31.5		
11	63.5			23.0		63.5	91.0	30.5		
10	63.0		64.0	22.0		62.5	90.5	29.5		57
9	62.0			21.5		62.0		29.0		
8	61.5		63.5	20.5		61.5	90.0	28.0		
7	61.0		63.0	20.0		61.0	89.5	27.0		56
6	60.5			19.5		60.5		26.0		
5	60.0		62.5	18.5		60.0	89.0	25.5		55
4	59.5		62.0	18.0		59.0	88.5	24.5		
3	59.0			17.0		58.5	88.0	23.5		
2	58.0		61.5	16.5		58.0		23.0		54
1	57.5		61.0	16.0		57.5	87.5	22.0		
0	57.0			15.0		57.0	87.0	21.0		53

** The 15-T, 30-T, 45-T, 15-N, 30-N, and 45-N values are in scales of the "Rockwell" Superficial Hardness Tester, a specialized form of "Rockwell" Tester, having lighter loads and more sensitive depth reading system, used where for one or another reason the indentation must be exceptionally shallow.

Wilson Chart 38 (*continued*) For hardened steel and alloys

C.	A.	D.	15-N **	30-N **	45-N **	Diamond Pyramid	Bri-nell	G.	Tensile Strength
“ROCKWELL” HARDNESS TESTER C scale “BRALE” penetrator Load	“ROCKWELL” HARDNESS TESTER A scale “BRALE” penetrator—60 kg Load	“ROCKWELL” HARDNESS TESTER D scale “BRALE” penetrator—100 kg Load	“ROCKWELL” SUPERFICIAL 15-N scale “N BRALE” penetrator—15 kg Load	“ROCKWELL” SUPERFICIAL 30-N scale “N BRALE” penetrator—30 kg Load	“ROCKWELL” SUPERFICIAL 45-N scale “N BRALE” penetrator—45 kg Load	4 sided 136° Diamond Pyramid 10 kg Load—Measurement of 2 diagonals by microscope. Hardness numbers computed by formula.	Brinell, Standard Type, 3000 kg Load Hultgren 10 mm Ball penetrator	“ROCKWELL” HARDNESS TESTER G scale 1/16″ Ball penetrator—150 kg Load	Thousand lbs per sq in.
80	92.0	86.5	96.5	92.0	87.0	1865			
79	91.5	85.5		91.5	86.5	1787			
78	91.0	84.5	96.0	91.0	85.5	1710			
77	90.5	84.0		90.5	84.5	1633			
76	90.0	83.0	95.5	90.0	83.5	1556			
75	89.5	82.5		83.0	82.5	1478			
74	89.0	81.5	95.0	88.5	81.5	1400			
73	88.5	81.0		88.0	80.5	1323			
72	88.0	80.0	94.5	87.0	79.5	1245			
71	87.0	79.5		86.5	78.5	1160			
70	86.5	78.5	94.0	86.0	77.5	1076			
69	86.0	78.0	93.5	85.0	76.5	1004			
68	85.5	77.0		84.5	75.5	942			
67	85.0	76.0	93.0	83.5	74.5	894			
66	84.5	75.5	92.5	83.0	73.0	854			
65	84.0	74.5	92.0	82.0	72.0	820			
64	83.5	74.0		81.0	71.0	789			
63	83.0	73.0	91.5	80.0	70.0	763			
62	82.5	72.5	91.0	79.0	69.0	739			
61	81.5	71.5	90.5	78.5	67.5	716			
60	81.0	71.0	90.0	77.5	66.5	695	614		314
59	80.5	70.0	89.5	76.5	65.5	675	600		306
58	80.0	69.0		75.5	64.0	655	587		299
57	79.5	68.5	89.0	75.0	63.0	636	573		291
56	79.0	67.5	88.5	74.0	62.0	617	560		284
55	78.5	67.0	88.0	73.0	61.0	598	547		277
54	78.0	66.0	87.5	72.0	59.5	580	534		270
53	77.5	65.5	87.0	71.0	58.5	562	522		263
52	77.0	64.5	86.5	70.5	57.5	545	509		256
51	76.5	64.0	86.0	69.5	56.0	528	496		250

Note:—General Conversion Values on material harder than about C-70 on the “Rockwell” Hardness Tester will probably be long in dispute because as yet there are few materials hard enough to be brought into that study and because some of those few do not flow nicely under the testing load but have a tendency to crumble and others do not approach homogeneity.

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C.	A.	D.	15-N **	30-N **	45-N **	Diamond Pyramid	Bri-nell	G.	Tensile Strength
“ROCKWELL” HARDNESS TESTER C scale “BRALE” penetrator Load	“ROCKWELL” HARDNESS TESTER A scale “BRALE” penetrator—60 kg Load	“ROCKWELL” HARDNESS TESTER D scale “BRALE” penetrator—100 kg Load	“ROCKWELL” SUPERFICIAL 15-N scale “N BRALE” penetrator—15 kg Load	“ROCKWELL” SUPERFICIAL 30-N scale “N BRALE” penetrator—30 kg Load	“ROCKWELL” SUPERFICIAL 45-N scale “N BRALE” penetrator—45 kg Load	4 sided 136° Diamond Pyramid 10 kg Load—Measurement of 2 diagonals by microscope. Hardness numbers computed by formula.	Brinell, Standard Type, 3000 kg Load Hultgren 10 mm Ball penetrator	“ROCKWELL” HARDNESS TESTER G scale 1/16″ Ball penetrator—150 kg Load	Thousand lbs per sq in.
50	76.0	63.0	85.5	68.5	55.0	513	484		243
49	75.5	62.0	85.0	67.5	54.0	498	472		236
48	74.5	61.5	84.5	66.5	52.5	485	460		230
47	74.0	60.5	84.0	66.0	51.5	471	448		223
46	73.5	60.0	83.5	65.0	50.0	458	437		217
45	73.0	59.0	83.0	64.0	49.0	446	426		211
44	72.5	58.5	82.5	63.0	48.0	435	415		205
43	72.0	57.5	82.0	62.0	46.5	424	404		199
42	71.5	57.0	81.5	61.5	45.5	413	393		194
41	71.0	56.0	81.0	60.5	44.5	403	382		188
40	70.5	55.5	80.5	59.5	43.0	393	372		182
39	70.0	54.5	80.0	58.5	42.0	383	362		177
38	69.5	54.0	79.5	57.5	41.0	373	352		171
37	69.0	53.0	79.0	56.5	39.5	363	342		166
36	68.5	52.5	78.5	56.0	38.5	353	332		162
35	68.0	51.5	78.0	55.0	37.0	343	322		157
34	67.5	50.5	77.0	54.0	36.0	334	313		153
33	67.0	50.0	76.5	53.0	35.0	325	305		148
32	66.5	49.0	76.0	52.0	33.5	317	297		144
31	66.0	48.5	75.5	51.5	32.5	309	290		140
30	65.5	47.5	75.0	50.5	31.5	301	283	92.0	136
29	65.0	47.0	74.5	49.5	30.0	293	276	91.0	132
28	64.5	46.0	74.0	48.5	29.0	285	270	90.0	129
27	64.0	45.5	73.5	47.5	28.0	278	265	89.0	126
26	63.5	44.5	72.5	47.0	26.5	271	260	88.0	123
25	63.0	44.0	72.0	46.0	25.5	264	255	87.0	120
24	62.5	43.0	71.5	45.0	24.0	257	250	86.0	117
23	62.0	42.5	71.0	44.0	23.0	251	245	84.5	115
22	61.5	41.5	70.5	43.0	22.0	246	240	83.5	112
21	61.0	41.0	70.0	42.5	20.5	241	235	82.5	110
20	60.5	40.0	69.5	41.5	19.5	236	230	81.0	108

The American Society for Testing Material's Conversion Tables E48–33T are not reproduced here as they are practically identical with the Wilson Conversion Chart No. 38, shown in this appendix. The full set of the American Society for Testing Material's tables may be obtained directly from the society headquarters in Philadelphia, Pennsylvania.

Hardness Conversion Table for Cartridge Brass (70 Per Cent Copper, 30 Per Cent Zinc Alloy)

Diamond Pyramid Hardness Number	Rockwell Hardness Number		Rockwell Superficial Hardness Number			Brinell Hardness Number
	B Scale, 100-kg Load, 1/16-in. Ball	F Scale, 60-kg Load, 1/16-in. Ball	15-T Scale, 15-kg Load, 1/16-in. Ball	30-T Scale, 30-kg Load, 1/16-in. Ball	45-T Scale, 45-kg Load, 1/16-in. Ball	500-kg Load, 10-mm Ball
45		40.0				42
46		43.0				43
47		45.0				44
48		47.0	53.5			45
49		49.0	54.5			46
50		50.5	55.5			47
52		53.5	57.0			48
54		56.5	58.5	12.0		50
56		58.8	60.0	15.0		52
58		61.0	61.0	18.0		53
60	10.0	63.0	62.5	20.5		55
62	12.5	65.0	63.5	23.0		57
64	15.5	66.8	65.0	25.5		59
66	18.5	68.5	66.0	28.0		61
68	21.5	70.0	67.0	30.0		62
70	24.5	71.8	68.0	32.0		63
72	27.5	73.2	69.0	34.0		64
74	30.0	74.8	70.0	36.0	1.0	66
76	32.5	76.0	70.5	38.0	4.5	68
78	35.0	77.4	71.5	39.5	7.5	70
80	37.5	78.6	72.0	41.0	10.0	72
82	40.0	80.0	73.0	43.0	12.5	74
84	42.0	81.2	73.5	44.0	14.5	76
86	44.0	82.3	74.5	45.5	17.0	77
88	46.0	83.5	75.0	47.0	19.0	79
90	47.5	84.4	75.5	48.0	21.0	80
92	49.5	85.4	76.5	49.0	23.0	82
94	51.0	86.3	77.0	50.5	24.5	83
96	53.0	87.2	77.5	51.5	26.5	85
98	54.0	88.0	78.0	52.5	28.0	86
100	56.0	89.0	78.5	53.5	29.5	88
102	57.0	89.8	79.0	54.5	30.5	90
104	58.0	90.5	79.5	55.0	32.0	92
106	59.5	91.2	80.0	56.0	33.0	94
108	61.0	92.0		57.0	34.5	95
110	62.0	92.6	80.5	58.0	35.5	97
112	63.0	93.0	81.0	58.5	37.0	99
114	64.0	94.0	81.5	59.5	38.0	101
116	65.0	94.5	82.0	60.0	39.0	103
118	66.0	95.0	82.5	60.5	40.0	105

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Hardness Conversion Table for Cartridge Brass (70 Per Cent Copper, 30 Per Cent Zinc Alloy) (*continued*)

Diamond Pyramid Hardness Number	Rockwell Hardness Number		Rockwell Superficial Hardness Number			Brinell Hardness Number
	B Scale, 100-kg Load, 1/16-in. Ball	F Scale, 60-kg Load, 1/16-in. Ball	15-T Scale, 15-kg Load, 1/16-in. Ball	30-T Scale, 30-kg Load, 1/16-in. Ball	45-T Scale, 45-kg Load, 1/16-in. Ball	500-kg Load, 10-mm Ball
120	67.0	95.5		61.0	41.0	106
122	68.0	96.0	83.0	62.0	42.0	108
124	69.0	96.5		62.5	43.0	110
126	70.0	97.0	83.5	63.0	44.0	112
128	71.0	97.5		63.5	45.0	113
130	72.0	98.0	84.0	64.5	45.5	114
132	73.0	98.5	84.5	65.0	46.5	116
134	73.5	99.0		65.5	47.5	118
136	74.5	99.5	85.0	66.0	48.0	120
138	75.0	100.0		66.5	49.0	121
140	76.0	100.5	85.5	67.0	50.0	122
142	77.0	101.0		67.5	51.0	124
144	77.5	101.5	86.0	68.0	51.5	126
146	78.0	102.0		68.5	52.5	128
148	79.0	102.5		69.0	53.0	129
150	80.0		86.5	69.5	53.5	131
152	80.5	103.0			54.0	133
154	81.5	103.5		70.0	54.5	135
156	82.0	104.0	87.0	70.5	55.5	136
158	83.0	104.5		71.0	56.0	138
160	83.5			71.5	56.5	139
162	84.0	105.0	87.5		57.5	141
164	85.0	105.5		72.0	58.0	142
166	85.5			72.5	58.5	144
168	86.0	106.0	88.0	73.0	59.0	146
170	87.0				59.5	147
172	87.5	106.5		73.5	60.0	149
174	88.0		88.5	74.0	60.5	150
176	88.5	107.0			61.0	152
178	89.0			74.5	61.5	154
180	90.0	107.5		75.0	62.0	156
182	90.5	108.0	89.0		62.5	157
184	91.0			75.5	63.0	159
186	91.5	108.5		76.0	63.5	161
188	92.0		89.5		64.0	162
190	92.5	109.0		76.5	64.5	164
192	93.0			77.0	65.0	166
194		109.5			65.5	167
196	93.5	110.0	90.0	77.5	66.0	169

Hardness Conversion Chart for Nickel and High-Nickel Alloys

Approximate Relationships Between Hardness Values Determined on the "Vickers," "Brinell," "Rockwell" and "Rockwell-Superficial" Testers

Vickers Hardness Numbers VHN	Brinell Hardness Numbers BHN	Rockwell Hardness Numbers (Scales as indicated below)								"Rockwell-Superficial" Hardness Numbers—(Scales as indicated below)					
		A	B	C	D	E	F	G	K	15-N	30-N	45-N	15-T	30-T	45-T
Diamond Pyramid Penetrator—1, 5, 10, 30 Kg Load, also 120 Kg Load with 2 mm Ball Penetrator	Standard Type—3000 Kg Load with 10 mm Ball Penetrator; also 500 Kg Load for Softer Metals	Diamond Cone "Brale" Penetrator, 60 Kg Load	1/16" Ball Penetrator 100 Kg Load	"Brale" Penetrator 150 Kg Load	"Brale" Penetrator 100 Kg Load	1/8" Ball Penetrator 100 Kg Load	1/16" Ball Penetrator 60 Kg Load	1/16" Ball Penetrator 150 Kg Load	1/8" Ball Penetrator 150 Kg Load	Sphero-Conical Diamond "N-Brale" Penetrator; 15 Kg Load	"N-Brale" Penetrator 30 Kg Load	"N-Brale" Penetrator 45 Kg Load	1/16" Ball Penetrator 15 Kg Load	1/16" Ball Penetrator 30 Kg Load	1/16" Ball Penetrator 45 Kg Load
513	479	75.5		50.0	63.0					85.5	68.0	54.5			
481	450	74.5		48.0	61.5					84.5	66.5	52.5			
452	425	73.5		46.0	60.0					83.5	64.5	50.0			
427	403	72.5		44.0	58.5					82.5	63.0	47.5			
404	382	71.5		42.0	57.0					81.5	61.0	45.5			
382	363	70.5		40.0	55.5					80.5	59.5	43.0			
362	346	69.5		38.0	54.0					79.5	58.0	41.0			
344	329	68.5		36.0	52.5					78.5	56.0	38.5			
326	313	67.5		34.0	50.5					77.5	54.5	36.0			
309	298	66.5	106	32.0	49.5		116.5	94.0		76.5	52.5	34.0	94.5	85.5	77.0
285	275	64.5	104	28.5	46.5		115.5	91.0		75.0	49.5	30.0	94.0	84.5	75.0
266	258	63.0	102	25.5	44.5		114.5	87.5		73.5	47.0	26.5	93.0	83.0	73.0
248	241	61.5	100	22.5	42.0		113.0	84.5		72.0	44.5	23.0	92.5	81.5	71.0
234	228	60.5	98	20.0	40.0		112.0	81.5		70.5	42.0	20.0	92.0	80.5	69.0
220	215	59.0	96	17.0	38.0		111.0	78.5	100.0	69.0	39.5	17.0	91.0	79.0	67.0
209	204	57.5	94	14.5	36.0		110.0	75.5	98.0	68.0	37.5	14.0	90.5	77.5	65.0
198	194	56.5	92	12.0	34.0		108.5	72.0	96.5	66.5	35.5	11.0	89.5	76.0	63.0

188	184	55.0	90	9.0	32.0	108.5	107.5	69.0	94.5	65.0	32.5	7.5	89.0	75.0	61.0
179	176	53.5	88	6.5	30.0	107.0	106.5	65.5	93.0	64.0	30.5	5.0	88.0	73.5	59.5
171	168	52.5	86	4.0	28.0	106.0	105.0	62.5	91.0	62.5	28.5	2.0	87.5	72.0	57.5
164	161	51.5	84	2.0	26.5	104.5	104.0	59.5	89.0	61.5	26.5	−0.5	87.0	70.5	55.5
157	155	50.0	82		24.5	103.0	103.0	56.5	87.5				86.0	69.5	53.5
151	149	49.0	80		22.5	102.0	101.5	53.0	85.5				85.5	68.0	51.5
145	144	47.5	78		21.0	100.5	100.5	50.0	83.5				84.5	66.5	49.5
140	139	46.5	76		19.0	99.5	99.5	47.0	82.0				84.0	65.5	47.5
135	134	45.5	74		17.5	98.0	98.5	43.5	80.0				83.0	64.0	45.5
130	129	44.0	72		16.0	97.0	97.0	40.5	78.0				82.5	62.5	43.5
126	125	43.0	70		14.5	95.5	96.0	37.5	76.5				82.0	61.0	41.5
122	121	42.0	68		13.0	94.5	95.0	34.5	74.5				81.0	60.0	39.5
119	118	41.0	66		11.5	93.0	93.5	31.0	72.5				80.5	58.5	37.5
115	114	40.0	64		10.0	91.5	92.5		71.0				79.5	57.0	35.5
112	111	39.0	62		8.0	90.5	91.5		69.0				79.0	56.0	33.5
108	108		60			89.0	90.0		67.5				78.5	54.5	31.5
106	106		58			88.0	89.0		65.5				77.5	53.0	29.5
103	103		56			86.5	88.0		63.5				77.0	51.5	27.5
100	100		54			85.5	87.0		62.0				76.0	50.5	25.5
98	98		52			84.0	85.5		60.0				75.5	49.0	23.5
95	95		50			83.0	84.5		58.0				74.5	47.5	21.5
93	93		48			81.5	83.5		56.5				74.0	46.5	19.5
91	91		46			80.5	82.0		54.5				73.5	45.0	17.0
89	89		44			79.0	81.0		52.5				72.5	43.5	14.5
87	87		42			78.0	80.0		51.0				72.0	42.0	12.5
85	85		40			76.5	79.0		49.0				71.0	41.0	10.0
83	83		38			75.0	77.5		47.0				70.5	39.5	7.5
81	81		36			74.0	76.5		45.5				70.0	38.0	5.5
79	79		34			72.5	75.5		43.5				69.0	36.5	3.0
78	78		32			71.5	74.0		42.0				68.5	35.5	1.0
77	77		30			70.0	73.0		40.0				67.5	34.0	−1.5

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Section III

Specifications for Different Hardness Tests

Various technical societies have prepared specifications for different hardness tests. These are not reproduced in full in this text because they are changed from time to time and it would be advisable for anyone interested in these specifications to secure the most up-to-date copy from the organization involved. The references are listed on the following page.

Title of the Specification	Number	Name and Address of Organization
Standard Method of Test for Brinell Hardness of Metallic Materials	E 10–27	American Society for Testing Materials, 260 S. Broad St., Phila., Pa.
Standard Methods of Test for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials	E 18–42	"
Tentative Method of End-quench Test for Hardenability of Steel	A 255–42T	"
Tentative Method of Test for Rockwell Hardness of Plastics and Electrical Insulating Materials	D 785–44T	"
Tentative Hardness Conversion Tables for Steel	E 48–43T	"
Diamond Pyramid Hardness Numbers	427: 1931	British Standards Institution, 28 Victoria Street, London, S.W. 1, England
British Standard Method and Tables for Brinell Hardness Testing	240 Part 1, 1937	"
The Hardness of Steel Balls for Brinell Hardness Testing	240 Part 2, 1929	"
Table of Approximate Comparison of Hardness Scales	860: 1939	"
Direct Reading Hardness Testing Rockwell Principle	891: 1940	"
National Bureau of Standards Specification for Knoop Indenters	Letter Circular LC 819	U. S. Dept. of Commerce National Bureau of Standards, Washington, D.C.
National Bureau of Standards Specification for Proving Rings for Calibrating Testing Machines	Letter Circular LC 822	"
Brinell Hardness Test		*Metals Handbook* 1948 Edition American Society for Metals 7016 Euclid Avenue, Cleveland, Ohio
Rockwell Hardness Test		
Scleroscope		
Monotron Hardness Test		
Vickers Hardness Test		
Bierbaum Microcharacter		
File Hardness Test		
Hardness Conversion Table		
Moh's Scale of Hardness		
Hardness Testing at Elevated Temperatures		
Eberbach Tester		
Tukon Tester		
King Portable Brinell		
Dynamic Tests		

Section IV

Hardness Values

Selecting the Most Suitable Steel for Tools

The tool engineers of the Westinghouse Electric & Mfg. Co. have made a thorough study of the different types of steel most suitable for different kinds of cutting tools. Through this study, they have reduced the number of tool steels used in the Westinghouse plant to hardly more than a dozen. This range of steel is applicable to any purpose—from dies for non-metallic materials to tools for performing all types of machining operations on steel.

The accompanying table "Composition of Steels Used for Tools" gives the range and composition of the different types of steel used, including carbon steel for tool shanks, carbon die steels, various alloy tool steels, and high-speed steels. The table shows eighteen grades; however, Grades 4, 6, 10, 13, and 18 are not carried regularly in stock, but are ordered as required for special applications.

In the following will be found a tabulated arrangement listing, alphabetically, different types of tools, and indicating the type of steel used by an identifying number that corresponds to the number given in the table specifying the composition, or a symbol explained in footnotes. The characteristics required for different types of tools, Rockwell hardness, and other data that may prove useful in making these tools are also given, all based upon the practice of the Westinghouse company.

The applications indicated are mainly for tools that are not met with in everyday shop practice in the ordinary plant. Plain turning tools, boring tools, and ordinary milling cutters, for example, are not referred to, since it is well known that, for such tools, either regular high-speed steel, cobalt high-speed steel, Stellite, or carbides may be employed, according to the machining requirements and conditions in each case.

Table 1. Composition of Steel used for Tools
Based on the Practice of the Westinghouse Electric & Mfg. Co.

No.	Class of Steel		Chemical Composition, Per Cent (Upper Line, Minimum; Lower Line, Maximum)										
			C	*Mn*	*P*	*S*	*Si*	*Ni*	*Cr*	*Va*	*W*	*Co*	*Mo*
1	Carbon Steel for Tool Shanks		0.50	0.60	....	....	0.15	....	....	....	....	....	....
			0.63	0.90	0.04	....	....	....	....	....	....	....	....
2	Tungsten High-Speed Steel		0.60	0.15	....	....	0.15	....	3.00	0.75	17.00	....	....
			0.75	0.40	0.03	0.03	0.40	....	4.50	1.50	19.00	....	....
3	Carbon Tool Steel		1.00	0.15	....	....	0.10	....	....	....	....	....	....
			1.10	0.35	0.025	0.025	0.35	....	....	....	....	....	....
4	Carbon Die Steel		0.80	....	....	....	....	....	....	....	....	....	....
			0.90	0.45	0.025	0.025	....	....	....	....	....	....	....
5	Carbon Steel Drill Rod	*	1.20	0.15	....	....	0.10	....	....	....	....	....	....
			1.35	0.35	0.025	0.025	0.25	....	....	....	....	....	....
		†	1.15	0.15	....	....	0.10	....	....	....	....	....	....
			1.30	0.35	0.025	0.025	0.25	....	....	....	....	....	....
		‡	1.10	0.15	....	....	0.10	....	....	....	....	....	....
			1.25	0.35	0.025	0.025	0.25	....	....	....	....	....	....
6	Oil-Hardening Non-Deforming		0.85	1.05	....	....	0.20	....	0.40	....	0.40	....	....
			0.95	1.25	0.025	0.025	0.35	....	0.60	0.25	0.60	....	....
7	Low-Tungsten, Chrome-Vanadium		1.15	0.20	....	....	0.20	....	0.35	0.15	1.30	....	....
			1.25	0.35	0.025	0.025	0.35	....	0.50	0.25	1.75	....	....
8	Chrome-Vanadium Steel		0.15	0.50	....	....	0.10	....	0.80	0.15	....	....	....
			0.25	0.80	0.04	0.04	0.20	....	1.10	0.25	....	....	....
9	Alloy Die-Block Steel		0.50	0.50	....	....	0.20	1.25	0.60	....	....	....	0.15
			0.60	0.80	0.04	0.04	0.30	1.75	0.80	0.12	....	....	0.25
			0.54	0.40	....	....	0.10	1.30	0.85	....	....	....	....
			0.66	0.50	0.03	0.03	0.20	1.60	1.10	....	....	....	....
10	Carbon Die-Block Steel		0.55	0.50	....	....	0.15	....	....	....	....	....	....
			0.65	0.70	0.04	0.04	0.30	....	....	....	....	....	....
11	Chrome-Vanadium Steel		0.45	0.50	....	....	....	....	0.80	0.15	....	....	....
			0.55	0.80	0.04	0.04	....	....	1.10	0.20	....	....	....
12	Low-Tungsten Alloy		0.40	0.15	....	....	0.15	....	1.25	0.15	2.00	....	....
			0.50	0.35	0.025	0.025	0.35	....	1.50	0.25	3.00	....	....
13	Tungsten Fast-finishing Steel		1.30	0.15	....	....	0.30	....	....	....	3.50	....	....
			1.45	0.25	0.025	0.025	0.60	....	0.50	....	5.00	....	0.50
14	Tungsten-Chromium Hot-Work Steel		0.32	0.10	....	....	0.20	....	3.00	0.30	9.75	....	....
			0.42	0.30	0.03	0.03	0.40	....	3.50	0.60	10.75	....	....
			0.32	0.20	....	....	0.20	....	3.25	0.60	13.50	....	....
			0.42	0.40	0.025	0.025	0.35	....	3.75	0.75	15.00	....	....
15	High-Carbon High-Chromium		1.45	0.20	....	....	0.20	....	11.00	....	....	0.40	0.70
			1.70	0.40	0.03	0.03	0.40	....	12.50	0.15	....	0.60	1.00
16	Cobalt High-Speed Steel		0.65	0.25	....	....	0.20	....	4.00	0.90	17.00	4.50	0.40
			0.75	0.35	0.03	0.03	0.40	....	4.25	1.10	18.00	5.00	0.50
			0.70	....	....	....	....	....	4.00	1.50	17.50	7.50	....
			0.80	0.40	0.04	0.025	0.50	....	5.00	2.25	19.50	10.00	1.00
17	Chrome-Vanadium		0.65	0.10	....	....	0.25	....	0.70	0.15	....	....	....
			0.75	0.30	0.03	0.03	0.35	....	0.90	0.25	....	....	....
18	Silicon-Molybdenum Steel		0.45	0.30	....	....	0.80	....	....	....	....	....	0.40
			0.55	0.50	0.02	0.02	1.10	....	....	....	....	....	0.60

* Up to ¼ inch, inclusive. † Over ¼ inch to ½ inch, inclusive. ‡ Over ½ inch.

Table 2. Steels to be used for Tools

See Table 1 for Composition of Steels

Kind of Tool	No. or Symbol of Steel	Qualities Wanted in Tool	Hardness, Rockwell C	Remarks
Arbor nuts, milling machine	11	Fair hardness, great strength	46–52	Grind after hardening
Arbors, balancing	3	Very hard	63–66	Grind after hardening
Arbors, milling machine, large-shank	C–N$_1$	Fair hardness, great strength	46–52	Grind after hardening
Arbors, milling machine, small-shank	11	Fair hardness, great strength	46–52	Grind after hardening
Arbors, up to 1¼ inches diameter	3	Very hard	63–66	Grind after hardening
Bender parts, for heavy plate	11	Fair hardness, great strength	46–52	Grind after hardening
Bender strippers and bender punch back pieces	17	Hardness, wear resistance, normal deformation	46–60	Finish to size and harden
Benders, for heavy materials, where parts are ground to size after hardening, due to hardening distortion	17	Hard surface and tough core, wear resistance, normal deformation	60–66	Grind after hardening
Benders, large area	17	Fair hardness, normal deformation	46–50	Finish to size and harden
Broaches	2	Maximum hardness, normal distortion, best cutting edge	63–65	Grind after hardening
Broaches, push, short	3	Very hard, keen cutting edges	63–66	Grind after hardening
Bushings, guide	H–R$_3$	Hard wearing surface, normal distortion	Rock. Super. 90 min. 15 N. scale	Grind after hardening
Buttons, locating	5	Very hard	63–66	Grind after hardening
Centers, lathe	3	Very hard	63–66	Grind after hardening
Chisels, cold, cutting end of	12	Shock and wear resistance	50–54	Grind after hardening
Chisels, cold; for chipping semihard die parts	3	Fair hardness, reduced brittleness	57–60	Grind after hardening
Chisels, pneumatic, shank end of; hand, hammer end of	12	Shock and wear resistance	46–48	Finish to size before hardening
Clamps	11	Medium hardness	46–52	Finish to size before hardening
Collars, milling machine arbor, with hole over 1½ inches in diameter	8	Hard case with semihard core, normal distortion, wear resisting	Rock. Super. 90 min. 15 N. scale	Grind after hardening

C–N$_1$, Chrome-nickel steel, with 0.30 to 0.40 per cent carbon.
H–R$_3$, Hot-rolled steel, with from 0.08 to 0.25 per cent carbon.

Table 2. Steels to be used for Tools (*continued*)

See Table 1 for Composition of Steels

Kind of Tool	No. or Symbol of Steel	Qualities Wanted in Tool	Hardness, Rockwell C	Remarks
Collets, front end of spring, that can be ground in the hole	3	Very hard in hole, shank drawn to Rockwell C37–41	63–66	Grind hole after hardening
Collets, not ground in the hole; draw shank end to 50–55 Scleroscope	7	Hardness, wear resistance, minimum distortion	60–63	Rough-machine, strain-relieve, finish to size, and harden
Counterbore pilots	3	Very hard	63–66	Grind after hardening
Counterbores	2	Maximum hardness, normal distortion best cutting edge	63–65	Grind after hardening
Cutters, drum; for woodwork	3	Toughness	50–54	Grind after hardening
Cutting tools for babbitt and nonferrous metals	3	Very hard, keen cutting edges	63–66	Grind after hardening
Cutting tools that can be ground after hardening	2	Maximum hardness, normal distortion, best cutting edge	63–65	Grind after hardening
Cutting tools; when impractical to grind	2	Maximum hardness, with minimum distortion, and good cutting edge	63–65	Rough-machine, strain-relieve, and finish to size before hardening
Die-blocks; maximum depth of impression, ⅜ inch; for high production and close tolerances	9	High production capacity, hardness	52–55	Finish to size before hardening
Die-blocks; maximum depth of impression, ⅝ inch; for high production and close tolerances	9	High production capacity, hardness	47–50	Finish to size before hardening
Die-blocks; maximum depth of impression, ¾ inch; for normal production with liberal tolerances; for simple impressions where sturdy tools can be employed	9	Normal production capacity, medium hardness, low-cost upkeep	41–43	Blocks may be bought heat-treated and the impression finish-machined in heat-treated block
Die-blocks; maximum depth of impression, 1 inch; for high production and close tolerances	9	High production capacity, hardness	44–46	Finish to size before hardening
Die-blocks; maximum depth of impression, 3 inches; for normal production with liberal tolerances	9	Normal production capacity, medium hardness, low-cost upkeep	38–41	Blocks may be bought heat-treated and the impression finish-machined in heat-treated block
Die-blocks; very deep impressions; for plastic molds or drop-forgings, especially forgings that will be machined to size	9	Normal production capacity, medium hardness, low-cost upkeep	35–37	Blocks may be bought heat-treated and the impression finish-machined in heat-treated block

Table 2. Steels to be used for Tools (*continued*)
See Table 1 for Composition of Steels

Kind of Tool	No. or Symbol of Steel	Qualities Wanted in Tool	Hardness, Rockwell C	Remarks
Die inserts for gear blanks, drop-forged	C–N_1	Medium hardness	37	Finish to size after hardening
Die parts, frail, that can be ground; for hard, thin, ferrous materials, and other materials 3/16 inch thick and over	2	Reduced brittleness, normal distortion, and reduced hardening risks	57–60	Grind after hardening
Die parts, frail, that can be ground; for mill-annealed steel	2	Toughness, normal distortion	31–36	Grind after hardening
Die parts, frail; when impractical to grind; for mill-annealed steel	2	Toughness and minimum distortion	31–36	Finish to size before hardening
Die parts, frail; when impractical to grind; for Nichrome and hard, thin, ferrous materials, as well as other materials 3/16 inch thick and over	2	Reduced brittleness, minimum distortion and hardening risks	57–60 57–60	Rough-machine, strain-relieve, and finish to size before hardening
Die parts, frail, where there is extreme risk of breakage or distortion in hardening; for soft, thin, ferrous materials	2	No distortion	28 max.	Finish to size, but do not harden
Die parts impractical to grind; for hard metals	15	Semi-hard	40–43	Finish to size before hardening
Die parts impractical to grind; for soft metals	15	Semi-hard	36–40	Finish to size before hardening
Die parts that can be ground, for hard metals	15	Semi-hard	40–43	Grind after hardening
Die parts that can be ground, for soft metals	15	Semi-hard, normal distortion	36–40	Grind after hardening
Die parts, medium hard, that can be ground; for ferrous material 1/16 inch thick and over; also for scaly iron and for steel with over 2.5 per cent silicon	2	Medium hardness, normal distortion	40–43	Grind after hardening
Die parts, medium hard; when impractical to grind; for ferrous materials 1/16 inch thick or over, for scaly iron and for steel with over 2½ per cent silicon	2	Medium hardness, minimum distortion and hardening risks	40–43	Finish to size before hardening
Die parts requiring surface hardness only	H–R_3	Surface hardness; hard surface approximately 0.004 inch thick	Rock. Super. 90 min. 15 N. scale	Finish to size before hardening; hard surface will not permit grinding; surface to be hardened must be machined

C–N_1, Chrome-nickel steel, with 0.30 to 0.40 per cent carbon.
H–R_3, Hot-rolled steel, with from 0.08 to 0.25 per cent carbon.

Table 2. Steels to be used for Tools (*continued*)

See Table 1 for Composition of Steels

Kind of Tool	No. or Symbol of Steel	Qualities Wanted in Tool	Hardness, Rockwell C	Remarks
Die parts requiring surface hardness only; surface will not permit grinding	C–R$_6$	Surface hardness; hardened surface approximately 0.004 inch thick	Rock. Super. 90 min. 15 N. scale	Anneal before machining, finish to size before hardening
Die parts, semi-hard, that can be ground; for steel with 2.5 per cent silicon or less, and for small blanking dies for steel	2	Semi-hard, normal distortion	36–40	Grind after hardening
Die parts, semi-hard; when impractical to grind; for steel with 2½ per cent silicon or less, and for small blanking dies for steel	2	Semi-hard, minimum distortion	36–40	Finish to size before hardening
Die parts, with weak sections, that can be ground; for hard, thin, ferrous materials	2	Freedom from breakage, normal distortion, and reduced hardening risks	52–55	Grind after hardening
Die parts with weak sections, when impractical to grind; for hard, thin, ferrous materials	2	Freedom from breakage, minimum distortion and hardening risks	52–55	Rough-machine, strain-relieve, and finish to size before hardening
Die strippers	H–R$_4$	Semi-hardness, machineability	29–33	Finish to size after hardening
Die strippers, compound, with stop lugs	17	Fair hardness, normal deformation	46–50	Finish to size and harden
Dies, bending and forming; for light materials	17	Maximum surface hardness, minimum distortion and breakage risks	63–66	Rough-machine, strain-relieve, finish to size, and harden
Dies, for copper, aluminum, and brass up to 0.020 inch thick for production of less than 50,000 pieces where tolerances are not close	H–R$_3$	Good cutting edges, minimum distortion, soft body	Rock. Super. 90 min. 15 N. scale	Largest dimension of punching not to be less than 3 inches
Die for heavy fuller-board, fiber, and mica	H–R$_3$	Good cutting edges, minimum distortion, soft body	Rock. Super. 90 min. 15 N. scale	Largest dimension of punching not to be less than 3 inches
Dies, for heavy plate materials	17	Hardness, wear resistance, normal deformation	54–57	Finish to size and harden
Dies for hot-pressing brass and copper alloys	14	Heat and wear resistance, minimum distortion	52–56	Rough-machine, strain-relieve, finish to size before hardening

C–R$_6$, Cold-rolled steel, with from 0.08 to 0.16 per cent carbon.
H–R$_4$, Hot-rolled steel, with from 0.30 to 0.45 per cent carbon.
H–R$_3$, Hot-rolled steel, with from 0.08 to 0.25 per cent carbon.

Table 2. Steels to be used for Tools (*continued*)

See Table 1 for Composition of Steels

Kind of Tool	No. or Symbol of Steel	Qualities Wanted in Tool	Hardness, Rockwell C	Remarks
Dies for punching and shearing hot metals	14	Heat and wear resistance, normal distortion	52–56	Grind after hardening
Dies, for rivet holes in structural steel	11	Fair hardness, great strength	51–55	Finish to size before hardening
Dies for small lots that can be ground	3	Hard, keen cutting edges	60–63	Grind after hardening
Dies impractical to grind; for hard, scaly, ferrous materials and non-ferrous materials of all thicknesses; for production between 5000 and 50,000 punchings	15	Hardness and toughness, minimum distortion, wear resistance	60–63	Rough-machine, strain-relieve, finish-machine, and harden
Dies impractical to grind; for quantities from 5000 to 50,000	7	Hardness, wear resistance, minimum distortion	60–63	Rough-machine, strain-relieve, finish to size, and harden
Dies impractical to grind; for silicon iron	15	Semi-hard	40–43	Finish to size before hardening
Dies that can be ground; for hard, scaly, ferrous materials and non-ferrous materials of all thicknesses; for production between 5000 and 50,000 punchings	15	Hardness and toughness, wear resistance, best quality cutting edge, normal distortion	60–63	Grind after hardening
Dies that can be ground; for silicon iron	15	Semi-hard	40–43	Grind after hardening
Dies, notching, shaving and for Nichrome	2	Maximum hardness, normal distortion, best cutting edge	63–65	Grind after hardening
Dies, notching, shaving, and for Nichrome	2	Maximum hardness, with minimum distortion, and good cutting edge	63–65	Rough-machine, strain-relieve, and finish to size before hardening
Dies, semi-hard, for small production; for all metals, paper, etc.	3	Semi-hard	31–36	Grind after hardening
Dies, shaving, that can be ground after hardening; for all scaly iron and for steel with over 2.5 per cent silicon	2	Hardness, normal distortion, best edge for die work	60–63	Grind after hardening
Dies, shaving; when impractical to grind; for all scaly iron, and for steel with over 2½ per cent silicon	2	Hardness, minimum distortion, and minimum hardening risk	60–63	Rough-machine, strain-relieve, and finish to size before hardening
Dies, straightening	17	Fair hardness, normal deformation	46–50	Finish to size and harden

Table 2. Steels to be used for Tools (*continued*)

See Table 1 for Composition of Steels

Kind of Tool	No. or Symbol of Steel	Qualities Wanted in Tool	Hardness, Rockwell C	Remarks
Dies, straightening and sizing; for cold drop-forgings	17	Hardness, wear resistance, maintenance of shape and size	57–60	Finish to size and harden
Dies, thread-rolling	15	Hardness and toughness, minimum distortion, wear resistance	60–63	Rough-machine, strain-relieve, finish-machine, and harden
Dies, trimming; for cold drop-forgings	2	Hardness, minimum distortion, and minimum hardening risk	60–63	Rough-machine, strain-relieve, and finish to size before hardening
Dies, trimming; for cold drop-forgings	2	Hardness, normal distortion, best edge for die work	60–63	Grind after hardening
Dies, trimming; for hot forging	11	Medium ductility, maximum machineability, hardness	30–35	Finish to size after hardening
Dies, trimming; for large hot forgings	C–Ni	Medium ductility, maximum machineability, hardness	30–35	Rough-machine; if necessary, harden; and finish to size after hardening
Drifts, round taper	12	Shock and wear resistance	46–48	Finish to size before hardening
Drifts, small	5	Toughness	45–48	Grind after hardening
Drill bushings, from 0.339- to 1½-inch diameter hole	3	Very hard	63–66	Grind after hardening
Drill bushings, plain and slip	8	Hard case with semi-hard core, normal distortion, wear resisting	Rock. Super. 90 min. 15 N. scale	Grind after hardening
Drill bushings, screw type	7	Hardness, wear resistance, minimum distortion	60–63	Rough-machine, strain-relieve, finish to size, and harden
Drill bushings, small	5	Very hard	63–66	Grind after hardening
Drill plates, multiple-hole	7	Hardness, wear resistance, minimum distortion	60–63	Rough-machine, strain-relieve, finish to size, and harden
Gage pins	5	Very hard	63–66	Grind after hardening
Gages, large thread, plug, and ring	C–Ni	Medium ductility, maximum machineability, hardness	30–35	Rough-machine; if necessary, harden; and finish to size after hardening
Gages, plug and ring; for spline-shaft and holes	7	Hard, wear-resisting surface; permanence of size, shape, and form	60–63	Rough-machine, normalize, harden, draw, rough-grind, season, and finish-grind

C–Ni, Chrome-nickel steel, with 0.30 to 0.40 per cent carbon.

Table 2. Steels to be used for Tools (*continued*)

See Table 1 for Composition of Steels

Kind of Tool	No. or Symbol of Steel	Qualities Wanted in Tool	Hardness, Rockwell C	Remarks
Gages, plug, plain and taper; from 4 to 12 inches in diameter	8	Hard case, wear resisting; permanence of size, shape, and form	Rock. Super. 90 min. 15 N. scale	Rough-machine, strain-relieve, finish-machine, harden, draw, rough-grind, season, finish-grind, and lap
Gages, plug thread; up to, but not including, ¼ inch diameter; all pitches; also gages ¼ to ⅜ inch diameter inclusive, with threads finer than 24 per inch	H–R$_8$	Hard surface approximately 0.003 inch thick, minimum distortion	Rock. Super. 90 min. 15 N. scale	Rough-machine, anneal, finish-machine, harden, and lap
Gages, plug thread, over ⅜ inch in diameter, with threads finer than 24 per inch	11	Medium ductility, maximum machineability, hardness	30–35	Finish to size after hardening
Gages, plug thread, with 24 threads per inch or coarser, ¼ inch to 4 inches diameter	7	Hard, wear-resisting surface; permanence of size, shape, and form	60–63	Rough-machine, normalize, harden, draw, rough-grind, season, and finish-grind
Gages, plug thread, over 4 inches in diameter	11	Medium ductility, maximum machineability, hardness	30–35	Finish to size after hardening
Gages, ring	H–R$_3$	Hard wearing surface, minimum distortion	Rock. Super. 90 min. 15 N. scale	Anneal, rough-machine, strain-relieve, finish-machine to size, and harden
Gages, ring, plain and taper, with hole over 1½ inches in diameter	8	Hard case, wear resisting; permanence of size, shape, and form	Rock. Super. 90 min. 15 N. scale	Rough-machine, strain-relieve, finish-machine, harden, draw, rough-grind, season, finish-grind, and lap
Gages, sheet steel, up to ⅛ inch thick inclusive, requiring partial or complete hardening	SS$_5$	Hardness, wear resistance	63–66	Grind after hardening
Gages, solid, plain; straight and tapered plug	3	Wear-resisting surface, permanence of size, shape. and form	63–66	Machine, harden, draw, rough-grind, season, finish-grind, and lap
Gages, spherical	3	Wear-resisting surface, permanence of size, shape, and form	63–66	Machine, harden, draw, rough-grind, season, finish-grind, and lap; same amount of stock must be removed on both sides

H–R$_8$, Hot-rolled steel, with from 0.08 to 0.18 per cent carbon.
H–R$_3$, Hot-rolled steel, with from 0.08 to 0.25 per cent carbon.
SS$_5$, Spring steel, with from 0.90 to 1.10 per cent carbon.

Table 2. Steels to be used for Tools (*continued*)

See Table 1 for Composition of Steels

Kind of Tool	No. or Symbol of Steel	Qualities Wanted in Tool	Hardness, Rockwell C	Remarks
Gages, straight and tapered ring	3	Wear-resisting surface, permanence of size, shape and form	63–66	Rough-machine, anneal, finish-machine, harden, draw, rough-grind, season, finish-grind and lap
Gear hobs	7	Hardness, wear resistance, minimum distortion	60–63	Rough-machine, strain-relieve, finish to size, and harden
Gear hobs; when impractical to grind	2	Maximum hardness, with minimum distortion, and good cutting edge	63–65	Rough-machine, strain-relieve, and finish to size before hardening
Gears	11	Medium ductility, maximum machineability, hardness	30–35	Finish to size after hardening
Gouges, cutting end of	12	Shock and wear resistance	50–54	Grind after hardening
Gouges, hammer end of	12	Shock and wear resistance	46–48	Finish to size before hardening
Guide pins	H–R$_3$	Hard wearing surface, normal distortion	Rock. Super. 90 min. 15 N. scale	Grind after hardening
Jigs, welded, under 60 pounds in weight	H–R$_4$	Semi-hardness, machineability	29–33	Finish to size after hardening
Mendrels, lathe	3	Very hard	63–66	Grind after hardening
Matrix, for large molds	H–R$_4$	Semi-hardness, machineability	29–33	Finish to size after hardening
Milling cutter bodies, inserted teeth	11	Medium ductility, maximum machineability, hardness	30–35	Finish to size after hardening
Milling cutter bodies, inserted teeth	C–N$_1$	Medium ductility, maximum machineability, hardness	30–35	Rough-machine; if necessary, harden; and finish to size after hardening
Milling cutter teeth, inserted	2	Maximum hardness, normal distortion, best cutting edge	63–65	Grind after hardening
Milling cutters, backed-off form; when impractical to grind	2	Maximum hardness, with minimum distortion, and good cutting edge	63–65	Rough-machine, strain-relieve, and finish to size before hardening

H–R$_3$, Hot-rolled steel, with from 0.08 to 0.25 per cent carbon.
H–R$_4$, Hot-rolled steel, with from 0.30 to 0.45 per cent carbon.
C–N$_1$, Chrome-nickel steel, with 0.30 to 0.40 per cent carbon.

Table 2. Steels to be used for Tools (*continued*)

See Table 1 for Composition of Steels

Kind of Tool	No. or Symbol of Steel	Qualities Wanted in Tool	Hardness, Rockwell C	Remarks
Milling cutters, dovetail	8	Hard case with semi-hard core, good wearing surface and cutting edge, minimum distortion	Rock. Super. 90 min. 15 N. scale	Rough-machine, strain-relieve, finish-machine, and harden
Milling cutters; ground after hardening	2	Maximum hardness, normal distortion, best cutting edge	63–65	Grind after hardening
Mold parts for plastic materials; impractical to grind; where material is not pinched off	3	Casehardened surface and semi-hard core, minimum distortion	Rock. Super. 90 min. 15 N. scale	Rough-machine, strain-relieve, and finish to size before hardening
Mold parts for plastics, ground after hardening	8	Hard case with semi-hard core, minimum distortion	Rock. Super. 90 min. 15 N. scale	Rough-machine, strain-relieve, finish to size, carburize, and harden
Molds, large; for molded materials	C–N_1	Medium ductility, maximum machineability, hardness	30–35	Rough-machine; if necessary, harden; and finish to size after hardening
Molds, permanent	14	Heat and wear resistance, minimum distortion	52–56	Rough-machine, strain-relieve, finish to size before hardening
Nuts, clamping	11	Medium ductility, maximum machineability, hardness	30–35	Finish to size after hardening
Pins for molds for plastics	5	Casehardened surface with semi-hard core, minimum distortion	Rock. Super. 90 min. 15 N. scale	Finish to size before hardening
Plungers; for bolt-heading machines	11	Fair hardness, great strength	46–52	Grind after hardening
Plungers, upsetting; for commutator bolts	11	Medium hardness	46–52	Finish to size before hardening
Plungers, upsetting; for nickel-steel shafts	11	Fair hardness, great strength	51–55	Finish to size before hardening
Punch backing plate for dies; over 5 inches in diameter	H–R_2	Fairly hard, normal distortion	44–48	Cut out by torch, anneal, machine, harden, and grind
Punches, center	3	Fair hardness, reduced brittleness	57–60	Grind after hardening
Punches, center, cutting end of	12	Shock and wear resistance	50–54	Grind after hardening
Punches, center, hammer end of	12	Shock and wear resistance	46–48	Finish to size before hardening

C–N_1, Chrome-nickel steel, with 0.30 to 0.40 per cent carbon.

H–R_2, Hot-rolled steel plate, with 0.30 to 0.45 per cent carbon.

Table 2. Steels to be used for Tools (*continued*)
See Table 1 for Composition of Steels

Kind of Tool	No. or Symbol of Steel	Qualities Wanted in Tool	Hardness, Rockwell C	Remarks
Punches for copper, aluminum, and brass up to 0.020 inch thick, for production of less than 50,000 pieces where tolerances are not too close	H–R$_3$	Semi-hard	36–40	Largest dimension of punching not to be less than 3 inches
Punches for heavy fullerboard, fiber, and mica	H–R$_3$	Good cutting edges, minimum distortion, soft body	Rock. Super. 90 min. 15 N. scale	Largest dimension of punching not to be less than 3 inches
Punches for heavy materials	3	Toughness	50–54	Grind after hardening
Punches for heavy plate materials	17	Hardness, wear resistance, normal deformation	54–57	Finish to size and harden
Punches for Nichrome	2	Reduced brittleness, normal distortion, and reduced hardening risks	57–60	Grind after hardening
Punches for small production; for all metals, paper, etc.	3	Semi-hard	31–36	Grind after hardening
Punches for soft materials	3	Fair hardness, reduced brittleness	57–60	Grind after hardening
Punches, semi-hard	5	Toughness	45–48	Grind after hardening
Punches, small piercing; under $^{11}/_{64}$ inch in diameter	CS$_7$	Hardness, shock and wear resistance	60–63	Grind after hardening
Punches, straight; for brass, copper, and insulation materials; shape impractical to grind	5	Reduction of brittleness	57–60	Finish to size before hardening
Punches, straight; ground after hardening; for brass, copper, and insulation materials	5	Reduction of brittleness	57–60	Grind after hardening
Reamers	2	Maximum hardness, normal distortion, best cutting edge	63–65	Grind after hardening
Reamers, hand	5	Very hard, keen cutting edge	63–66	Grind after hardening
Reamers, long; hand and line, and large taper	8	Hard case with semi-hard core, good wearing surface and cutting edge, minimum distortion	Rock. Super. 90 min. 15 N. scale	Rough-machine, strain-relieve, finish-machine, and harden
Rivet punch guide plates	17	Fair hardness, normal deformation	46–50	Finish to size and harden
Rivet sets, cold	17	Hardness, wear resistance, normal deformation	46–60	Finish to size and harden

H–R$_3$, Hot-rolled steel, with from 0.08 to 2.25 per cent carbon.
CS$_7$, Carbon steel, No. 9 temper, with from 0.86 to 0.95 per cent carbon.

Table 2. Steels to be used for Tools (*continued*)

See Table 1 for Composition of Steels

Kind of Tool	No. or Symbol of Steel	Qualities Wanted in Tool	Hardness, Rockwell C	Remarks
Rivet sets, large	11	Medium hardness	46–52	Finish to size before hardening
Rivet setting tools, forming end of	12	Shock and wear resistance	40–43	Finish to size before hardening
Saws and notching dies for Nichrome	2	Maximum hardness, normal distortion, best cutting edge	63–65	Grind after hardening
Saws, cutting-off, high-speed steel teeth for	2	Hard cutting end, with shank soft	61–63	Grind after hardening
Scrapers, for copper wire	SS_5	Spring temper, wear resistance	46–48	Grind after hardening
Screwdrivers	12	Shock and wear resistance	46–48	Finish to size before hardening
Shear blades, small	3	Fair hardness, reduced brittleness	57–60	Grind after hardening
Stamps, lettering and numbering	3	Fair hardness, reduced brittleness	57–60	Grind after hardening
Stripper fingers, long, thin	17	Fair hardness, normal deformation	46–50	Finish to size and harden
Taps, ground-thread	2	Maximum hardness, normal distortion, best cutting edge	63–65	Grind after hardening
Taps, not ground in thread	7	Hardness, wear resistance, minimum distortion	60–63	Rough-machine, strain-relieve, finish to size, and harden
Templets, sheet steel	SS_5	Hardness, wear resistance	63–66	Grind after hardening
Tool-holders	11	Medium ductility, maximum machineability, hardness	30–35	Finish to size after hardening
Tools requiring great pressure on small areas	17	Hardness, wear resistance, normal deformation	46–60	Finish to size and harden
V-blocs	H–R_3	Hard wearing surface, normal distortion	Rock. Super. 90 min. 15 N. scale	Grind after hardening
Vise jaws	H–R_3	Hard wearing surface, minimum distortion	Rock. Super. 90 min. 15 N. scale	Anneal, rough-machine, strain-relieve, finish-machine to size and harden
Welding scale removing tools	12	Shock and wear resistance	46–48	Finish to size before hardening
Woodworking tools	3	Toughness	45–48	Grind after hardening
Wrenches, special	11	Medium ductility, maximum machineability, hardness	30–35	Finish to size after hardening

SS_5, Spring steel, with from 0.90 to 1.10 per cent carbon.
H–R_3, Hot-rolled steel, with from 0.08 to 0.25 per cent carbon.

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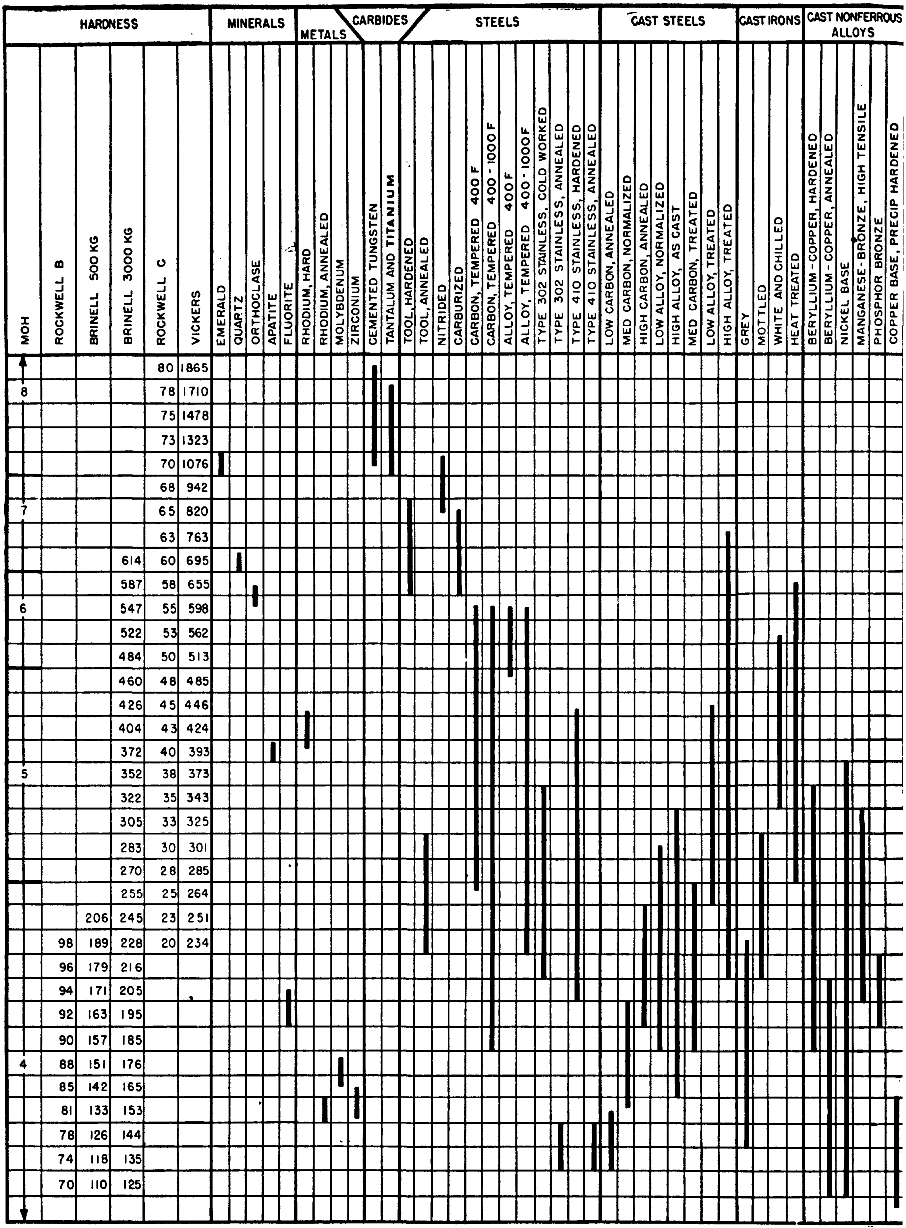
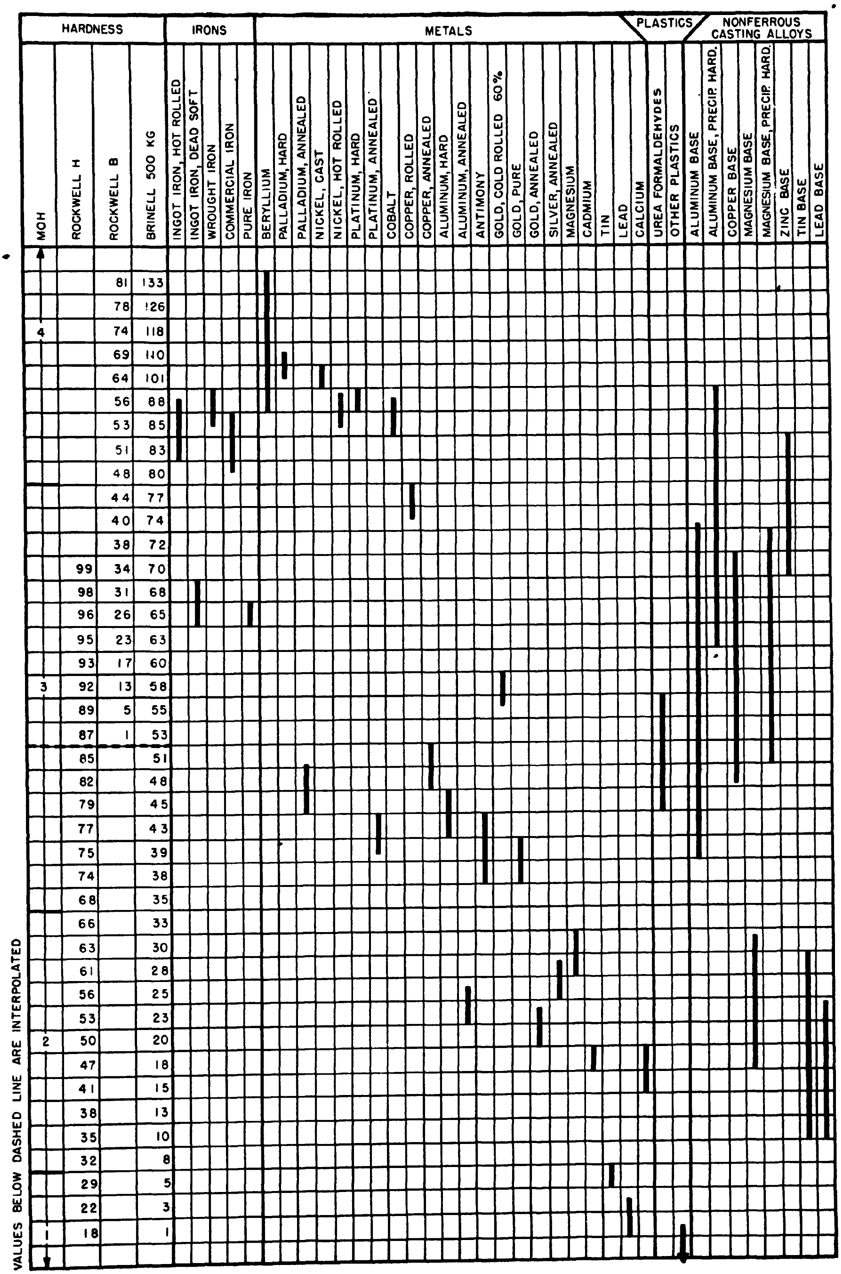
Hardness Ranges For Various Metals



COMPILED BY S.D. SMOKE DATA BASED ON THE PURDUE UNIVERSITY CHART, "VICKERS, ROCKWELL AND BRINELL HARDNESS VALUES FOR VARIOUS MATERIALS AND ALLOYS" BY J.T. AGNEW, NOW RESEARCH ENGINEER, THE FRANKLIN INSTITUTE.

Hardness Ranges For Various Metals



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