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HARDNESS

Hardness is a measure of a material's resistance to deformation. In this article hardness is taken to be the measure of a material's resistance to indentation by a tool or indenter harder than itself. This seems a relatively simple concept until mathematical analysis is attempted; the elastic, plastic, and elastic recovery properties of a material are involved, making the relationship quite complex. Further complications are introduced by variations in elastic modulus and frictional coefficients.

As a consequence, although the precise analysis of the indentation process continues, numerous practical applications of indentation hardness are in use and others are being developed. The impetus to this development is that whatever the numerical value of indentation hardness, it is clearly related to many other material properties of greater interest to engineers such as strength, wear resistance, and machinability. The relationship to the strength properties of materials is the most important. The indentation hardness test provides at once a simple, rapid, and essentially nondestructive means of testing a material and discovering its strength.

A hardness indentation causes both elastic and plastic deformations which activate certain strengthening mechanisms in metals. Dislocations created by the deformation result in strain hardening of metals. Thus the indentation hardness test, which is a measure of resistance to deformation, is affected by the rate of strain hardening.

Anisotropy in metals and composite materials is common as a result of manufacturing history. Anisotropic materials often display significantly different results when tested along different planes. This applies to indentation hardness tests as well as any other test.

Many types of hardness tests have been devised. The most common in use are the static indentation tests, eg, Brinell, Rockwell, and Vickers. Dynamic hardness tests involve the elastic response or rebound of a dropped indenter, eg, Scleroscope (Table 1). The approximate relationships among the various hardness tests are given in Table 2.

Although indentation hardness tests are usually classified as nondestructive they do in fact leave a permanent indentation on the surface of the workpiece. Thus the nondestructiveness of indentation hardness testing depends on the criticality of the tested surface and the location of the indentations.

1. Indentation Tests

1.1. Brinell

The first reliable indentation hardness test was developed by Brinell in 1900 and used ball bearings to make indentations in steel (1). The technique has remained reliable and essentially unchanged for nearly 100 years. The test, described by ASTM Standard E10 (2), is still in use.

The principle of the Brinell hardness test is that the spherical surface area of a recovered indentation made with a standard hardened steel ball under specific load is directly related to the property called hardness. In the following, HBN = Brinell hardness number, P = load in kgf, D = diameter of the ball in mm, and

Table 1. Hardness Tests Described by ASTM Standards

Common name	Title	ASTM number[a]
Brinell	Brinell Hardness of Metallic Materials	E10
Rockwell	Rockwell Hardness and Rockwell SuperficialHardness of Metallic Materials	E18
Vickers DPH	Test Method for Vickers Hardness of MetallicMaterials	E92
Knoop/DPH	Test Method Microhardness of Materials	E384
Scleroscope	Recommended Practice for ScleroscopicHardness Testing of Metallic Materials	E448
InternationalRubber	Test Method for Rubber Property InternationalHardness	D1415
Durometer	Test Method for Rubber Property DurometerHardness	D2240
Barcol	Test Method for Indentation Hardness of RigidPlastics via Barcol Impresser	D2583
Portable	Test Method for Indentation Hardness of Metalusing Portable Hardness Testers	E110
Webster	Webster Hardness Gauge	B647

[a]Ref. 2.

Table 2. Approximate Relation Between Hardness Scales[a]

		Rockwell		Superficial			
Vickers	Brinell	B	C	15 N	30 N	Knoop	Scleroscope
900			67	92.9	83.6	895	95
800	722		64	91.8	81.1	822	88
700	656		60.1	90.3	77.6	735	81
600	564		55.2	88.0	73.2	636	74
500	471		49.1	85.0	67.7	528	66
400	379		40.8	80.8	60.2	412	55
300	284		29.8	74.9	50.2	309	42
250	238	99.5	22.2	70.6	43.4	262	36
200	190	91.5				216	29
150	143	78.7				164	22
100	95	56.2				112	

[a]This table shows the relationship between hardness testing scales, but should not be used for hardness converson. See ASTM E140 (2) for specific materials conversions.

d = diameter of the impression in mm. (For load expressed in Newtons, the denominator must be $9.807\pi D$ … to obtain the same HBN).

$$\text{HBN} = \frac{2P}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$$

In commercial practice a 10-mm steel ball is considered standard, although other diameters may be used, and a 29.4 kN (3000 kgf) load is most common. Lesser loads are used for materials softer than steel such as aluminum and copper.

Because of the geometric limitations of the indenting ball the relationship between indentation area and computed hardness number deviates from linearity when the recovered indentation diameter of a 10-mm ball is less than 2.5 mm or greater than 6.0 mm.

In practice it is still necessary to read the diameter of the Brinell impressions with a calibrated microscope; however, the computations to derive the Brinell hardness number are unnecessary for standard loads and indentors. Table 1 of ASTM E10 (2) contains the tabulated relation between indentation diameter and hardness number.

Test pieces for Brinell testing must have two parallel sides and be reasonably smooth for proper support on the anvil of the test machine. Minimum sample thickness must be 10 times indentation depth. Successive indentations must not be closer than three indentation diameters to one another or to the edge of the test piece.

Thus the Brinell test in its original manifestation is a laboratory test in which cut pieces are brought to it for testing. The lack of portability spawned several modifications to achieve that property.

The simplest of the portable modifications is a lightweight version of the original machine in which the hydraulic loading system is replaced by a spring. This machine still requires a sample be cut from large pieces for testing.

The pin Brinell tester takes the form of a large C clamp with the ball indenter on the end of the screw. Load is controlled by a built-in shear pin. A modification of this device employs impact loading by a hammer to achieve similar results.

There are also strap-on type Brinell testers in which the anvil is supplanted by a chain or other clamping device and the indenter is spring-loaded. These have the advantage of being able to test directly very large objects without the need for cutting samples.

The hand-held comparative Brinell tester is the most portable device. With this device a hammer blow is substituted for the static load which is transmitted first through a standard bar of known hardness and then through the indenter into the workpiece. The indentations in both the standard bar and the workpiece are measured and from the ratio of the diameters the HBN is derived. The loss in accuracy is made up for by the excellent portability.

The latest portable Brinell testers are spring-loaded, hand-held, and digitized to read directly in Brinell hardness units. Their accuracy is questionable because of extreme surface sensitivity and they are not in fact Brinell testers but Rockwell indenters calibrated to read in Brinell numbers.

The Brinell test range is limited, by the capability of the hardened steel ball indenters used, to HBN 444. This range can be extended upward to HBN 500 by using special cold work-hardened steel balls and to as high as HBN 627 by using special tungsten carbide balls.

Standard practice for Brinell testing is to measure the diameter of each indentation twice and average the measurement before entering the tables to determine HBN. The same averaging principle is applied on nonflat (curved) surfaces which yield an elliptical, not a round, indentation.

1.2. Rockwell

The invention of the Rockwell hardness tester in 1919 was an advance over previous indentation tests requiring accurate indentation measurement and tabular reduction to derive a hardness number. In the Rockwell test the hardness number is read directly from the instrument dial (1, 3).

The principle of the Rockwell hardness test is that the depth of the indentation between a minor and a major load applied through an indenter is inversely proportional to the hardness number. Using a minor load to set the indenter helps to reduce backlash in the measuring system.

In the Rockwell test a spheroconical diamond (Brale) indenter or a hardened steel ball is used with various load ranges to achieve a series of scales identified by a suffix letter (Table 3). The suffix letter defines both load and indenter. The most popular scales used are “C” for hard materials and “B” for soft materials. A Rockwell hardness number is meaningless without the letter suffix, eg, HRC 54 or HRB 95.

The Rockwell testing machine is thus a framework permitting stable support of the workpiece on one side and means to impress the indenter under specified load on the other. A dial indicator attached to the indenter spindle is used to read directly the depth of indentation in hardness numbers.

The relationship between depth of penetration and the Rockwell hardness number is

$$\mathrm{HRC} = \mathrm{C} - (d/0.002)$$

Table 3. Rockwell Hardness Testing Scale Designations

	Major[b] load, N[c]		
Indenter[a]	588	98	1471
Brale[d]	A	D	C
1.6 mm ball	F	B	G
3.2 mm ball	H	E	K
6.4 mm ball	L	M	P
12.7 mm ball	R	S	V

[a]Hardened steel balls of various diameters are used for materialssignificantly softer than the ball itself. Brale[d] penetrators are used forharder materials.
[b]Minor load is $98\ \mathrm{N} = 10\ \mathrm{kgf}$ for all scales.
[c]To convert N to kgf, divide by 9.807.
[d]A spheroconical diamond indenter having a 120° included cone angle.

where HRC = Rockwell C hardness number, C = indenter constant (100), and d = depth indentation in mm. Similarly the relationship for Rockwell B hardness is

$$\mathrm{HRB} = \mathrm{B} - (d/0.002)$$

where HRB = Rockwell B hardness number, B = ball constant 130, and d = depth indentation in mm. This relationship is most often used in computing minimum sample thicknesses which for Rockwell tests is a minimum of 10 times indentation depth.

The A, D, and C Rockwell scales used primarily for steel and hard materials yield hardness numbers from 20 to about 85. Hardness numbers lower than HRC 20 are invalid; the Rockwell B, G, or F scales should be used. Hardness conversions from one scale to another are available for some common materials. (see Table 4, ASTM E140)

The Rockwell superficial test was developed to accommodate smaller and thinner samples than the standard Rockwell test. The test principle is identical to the standard Rockwell test but the major and minor loads are substantially smaller. The test machine is also similar but modified to accommodate the smaller loads. Dual purpose machines can handle both standard and superficial tests.

The indenter/load combinations used for superficial Rockwell testing are listed in Table 5. As with the standard Rockwell test it is necessary to include the superficial load/indenter combination used for the hardness number to be meaningful, eg, HR30N 65 or HR30T 65.

Most laboratory and shop-use Rockwell hardness testers are nonportable, lever operated, deadweight machines. Newer versions have digital readouts rather than the traditional analogue dial. Some designs of Rockwell testers employ a spring-loading system instead of deadweights.

Portable hand-held direct reading Rockwell testers have been developed and are in use, as are numerous C clamp configurations, all intended for field or shop use. The newest computerized digital readout Rockwell tester provides the ultimate in portability at the cost of some loss of sensitivity due to the very light loads used.

The standard Rockwell test requires a relatively smooth surface (120 grit or better) for reproducibility. Superficial Rockwell test samples must be ground to 600 grit or better for accuracy and reproducibility.

Although the Rockwell test is intended to be used on flat parallel-sided specimens, its use can be extended to rounded surfaces by using a curvature correction factor. Compound surfaces such as gear teeth can be tested but the results must be corrected for curvature.

Table 4. ASTM Standards Related to Hardness Testing[a]

ASTM number	ASTM standard
A370	Brinell Tests of Steel Products
A833	Comparison Hardness Tester Practice
B294	Rockwell Test on Cemented Carbides
B347	Rockwell Test for Sintered Materials
B578	Knoop Test for Electrodeposited Coatings
B647	Webster Hardness Gauge
B648	Barcol Test of Aluminum Alloys
B724	Newage Portable Hardness Tests for Aluminum Alloys
C569	Indentation Test for Thermal Insulation
C661	Durometer Test for Elastomeric Sealants
C730	Knoop Test for Glass
C748	Rockwell Test for Graphitic Materials
C849	Knoop Test on Ceramic Whitewear
C886	Scleroscope of Carbon and Graphite
D1414	Hardness Tests on Rubber O-Rings
D1415	Test Method for Rubber Property–International Hardness
D2240	Test Method for Rubber Property–Durometer Hardness
D2583	Test Method for Indentation Hardness of Rigid Plastics by Meansof Barcol Impressor
D617	Rockwell Test for Phenolic Laminated Sheet
D785	Rockwell Test on Electrical Insulating Materials
E92	Test Method for Vickers Hardness of Metallic Materials
E103	Rapid Indentation Hardness Tests
E384	Test Method for Microhardness of Materials
E1077	Test for Decarburization of Steel
E140	Hardness Conversion Tables for Metals
E448	Recommended Practice for Scleroscope Hardness Testing MetallicMaterials
F451	Rockwell Hardness of Bone Cements
F500	Hardness of Neurosurgical Acrylic Resin

[a]Ref. 2.

Table 5. Rockwell Hardness Testing Scale Designations

	Major[b] load, N[c]		
Indenter[a]	147	294	441
Brale[d]	15N	30N	45N
1.6 mm ball	15T	30T	45T
3.2 mm ball	15W	30W	45W
6.4 mm ball	15X	30X	45X
12.7 mm ball	15Y	30Y	45Y

[a]Hardened steel balls of various diameters are used for materialssignificantly softer than the ball itself. Brale[d] penetrators are used forharder materials.
[b]Minor load for all scales is $29.4\ N = 3\ kgf$.
[c]To convert N to kgf, divide by 9.807.
[d]A spheroconical diamond indenter having a 120° included cone angle.

As with all tests, frequent calibration of the test equipment using standard hardness blocks is a prerequisite for reliable hardness testing (see ASTM E18). Standard hardness blocks are available through commercial sources in the United States but do not have traceability to internationally accepted standards as in Europe.

Rockwell hardness testing has been extended to both low and high temperature regimes usually by enclosing the sample and part of the machine in an environmental chamber and using extensions for the anvil and indenter.

Recommended procedures for use with Rockwell and superficial Rockwell tests are detailed in ASTM E18 (2).

1.3. Vickers Hardness

The Vickers or diamond pyramid hardness (DPH) developed in 1924 was an improvement over the Brinell test. The Vickers test used a pyramidal diamond as the indenter. This permitted the hardness testing of much harder materials, and the constant 136° angle of the indenter eliminated the problem of variable indentation shape encountered using spherical indenters (1).

Vickers hardness numbers are calculated from measurement of the indentation diagonals as follows, where HV = Vickers hardness, P = applied load in N, D = indentation diagonal in mm, and $\theta = 136^\circ$. For load in kgf, omit 9.807 in the denominator.

$$\mathrm{HV} = \frac{2P\sin(\theta/2)}{9.807\ D^2} \quad \text{or} \quad = \frac{1.8544\ P}{9.807\ D^2}$$

The Vickers hardness test is a macrohardness test in which loads are commonly varied from 9.8 to 1180 N (1 to 120 kgf). Vickers hardness numbers are invariant with load within the stated limits.

The Vickers hardness test is commonly made on a flat specimen on which the indenter is hydraulically loaded. When the desired number of indentations have been made, the specimen is removed and both diagonals of the indentations, measured using a calibrated microscope, are then averaged. The Vickers hardness number may be calculated, or for standard loads taken from a precalculated table of indentation size vs VHN. The preferred procedures are described in ASTM E92 (2).

The Vickers hardness test, developed in the United Kingdom, is more popular there than in the United States. VHN (Vickers hardness number) and DPH (diamond pyramid hardness) are synonymous terms.

Surface finish requirements for the Vickers test vary with the test load. Heavy load tests can be made on a 120 grit ground surface. At low loads increasingly finer surface preparation is required, approaching that for metallographic specimens, to permit accurate diamond indentation measurements.

Minimum thickness requirements are 1 1/2 times the indentation diagonal measurement, and there should be no visible marking or bulge visible on the side opposite the indentation. The Vickers test is based on a plane surface; however, correction tables are available for both convex and concave surfaces (see ASTM E92) (2).

Conversion to other hardness scales from Vickers is approximated for specific materials listed in ASTM E140 (2). Conversions outside the stated areas should be avoided unless supported by test data.

1.4. Microhardness

Given a sufficiently accurately ground Vickers diamond indenter, and the load insensitivity of the Vickers test, a natural extension of this technology has been to reduce loads to less than 9.8 N (1 kgf). The load limit defines the area called microhardness testing (ASTM E384). To accomplish this test, machines capable of accurately applying loads as low as 9.8 mN (1 gf) have been developed. All use the Vickers 136 diamond indenter. This development permits the determination of the hardness of discrete metallurgical or mineralogical constituents not previously possible with macrohardness techniques (4).

In 1939 the Rhomb-shaped diamond indenter, having a length-to-breadth ratio of 7:1, was introduced to microhardness testing (5). The advantages of the Knoop indenter are that it requires measurement of only the long diagonal of the indentation and it is said to be more sensitive and accurate when used on highly recoverable materials such as glass.

In time most commercially available microhardness testers accepted both Vickers and Knoop indenters. The Vickers remained almost universally used in Europe but shared acceptance with the Knoop in the United States.

The Knoop hardness number is computed from the measured long diagonal by the following formula where HK = Knoop hardness, P = load in Newtons, and d = long diagonal, mm.

$$\mathrm{HK} = \frac{14229\,P}{d^2}$$

All microhardness testing machines are touchy to operate owing to the very small loads involved and the danger of inertial effects when loading. In addition it has been found that the duration of load application affects results. Commercial testers, therefore, have automatic load/unload cycles and interval timers. More modern versions have autodata recording and in some cases programmable sequences of indentation locations. Microhardness testing due to the careful sample preparation required (metallographic polish) and the delicacy of the test apparatus, is a laboratory test only.

Applications of microhardness testing greatly extend the conventional indentation hardness test to glass and ceramics, metallographic constituents, and to thin coatings or other surface treatments not otherwise testable.

The shortcomings of microhardness tests include numerous sources of errors not found in macrohardness tests such as friction, vibration, inertia, windage, and the skill of the test operator.

1.5. Ultrasonic Microhardness

A new microhardness test using ultrasonic vibrations has been developed and offers some advantages over conventional microhardness tests that rely on physical measurement of the remaining indentation size (6). The ultrasonic method uses the DPH diamond indenter under a constant load of 7.8 N (800 gf) or less. The hardness number is derived from a comparison of the natural frequency of the diamond indenter when free or loaded. Knowledge of the modulus of elasticity of the material under test and a smooth surface finish is required. The technique is fast and direct-reading, making it useful for production testing of similarly shaped parts.

1.6. Scratch Hardness

1.6.1. Mohs'

An early (1822) hardness comparison test involved assigning a relative number to all known materials (usually minerals and pure metals) by virtue of their relative ability to scratch one another. The results of this classification are not relatable to other properties of materials or to other measures of hardness. As a result of this limited usefulness, the Mohs' hardness test is primarily used for mineral identification. Some examples of the Mohs' hardness scale, which ranks materials from 1 to 10, are listed in Table 6.

1.6.2. Scratch Test

The scratch microhardness test is a refinement of the Mohs' test. The corner of a cubic diamond is drawn across the surface of a metallographically polished sample under a constant load, usually 29.4 N (3 kgf). The width of the resultant Vee groove scratch varies inversely with the hardness of the material displaced where

Table 6. Mohs' Hardness Numbers for SomeMaterials

Mohs' hardness	Material
1	talc/graphite
2	cadmium/anthracite
3	calcite/boric acid
4	bell metal/fluorite
5	manganese/asbestos
6	feldspar/pumice
7	flint/quartz
8	topaz/beryl
9	corundum/chromium
10	carbon/diamond

H = scratch hardness number and λ = groove width in micrometers.

$$H = \frac{10000}{\lambda^2}$$

This test finds application on finely polished and/or etched metallographic samples and mineralogical samples. It is useful for distinguishing variations in hardness between adjacent microconstituents. The test is extremely delicate and therefore is little used commercially. Use is largely restricted to research institutions. There is no established means of converting scratch hardness data to other hardness scales.

1.7. Sceleroscope Rebound Tests

The Scleroscope is a rebound-type hardness tester invented in 1907 (7). The principle involves dropping a diamond-tipped hammer from a specified height onto the test piece and measuring the height of rebound. In practice the hammer or drop weight is enclosed in a calibrated glass tube, raised by air pressure, then dropped. Rebound height is read from a scale on the glass tube. Later models of the Scleroscope contain a friction clutch that stops the hammer at the maximum point of rebound for easier reading. Preferred test procedures are described in ASTM E448 (2).

The Scleroscope scale ranges from 0 to 140; the calibration point of 100 is the hardness of fully quenched but untempered steel. Standard test blocks embodying this condition are used for calibration.

Portability, simplicity, and high speed are the main advantages of this portable hardness tester. It uses a single numerical scale encompassing the hardness of all metals.

Friction due to lack of vertical positioning of the tube is a source of error, as is sensitivity to the surface condition of the test piece. Samples of small mass cannot be tested except when supported on a heavy anvil.

Scleroscope hardness numbers are convertible to other hardness scales (see ASTM E140) (2).

2. Special-Purpose Testers

2.1. Barcol Indenter

The Barcol hardness tester is a hand-held, spring-loaded instrument with a steel indenter developed for use on hard plastics and soft metals (ASTM D2583) (2). In use the indenter is forced into the sample surface and a hardness number is read directly off the integral dial indicator calibrated on a 0 to 100 scale. Barcol hardness numbers do not relate to nor can they be converted to other hardness scales. The Barcol instrument is calibrated at each use by indenting an aluminum alloy standard disk supplied with it. The Barcol test is relatively insensitive to surface condition but may be affected by test sample size and thickness.

2.2. Durometer

The Durometer hardness test was developed for and is used for determining the hardness of elastomers. The Durometer is a hand-held, spring-loaded instrument which when pressed against the sample forces a conical steel indenter into the surface. Durometer hardness numbers range from 0 to 100 and are read directly from the attached dial indicator. Several load scales are available, but the A scale (8 N = 822 gf) and the D scale (44.5 N = 4.54 kgf) are most common. Specifics of the test procedure are discussed in ASTM D2240 (2). Lighter load scales and larger diameter indenters are available for very soft materials such as foam.

Operator skill and experience are necessary to obtain consistent results using a Durometer. Speed of load application, dwell time, and sample thickness can affect reproducibility of results. Durometer calibration prior to each test series is done using a test block provided with the instrument. When large numbers of tests are required, improved consistency of results are obtained if the Durometer is used with the accessory vertical stand rather than hand held.

2.3. International Rubber Hardness

The International rubber hardness test (ASTM D1415) (2) for elastomers is similar to the Rockwell test in that the measured property is the difference in penetration of a standard steel ball between minor and major loads. The viscoelastic properties of elastomers require that a load application time, usually 30 seconds, be a part of the test procedure. The hardness number is read directly on a scale of 0 to 100 upon return to the minor load. International rubber hardness numbers are often considered equivalent to Durometer hardness numbers but differences in indenters, loads, and test time preclude such a relationship.

2.4. Webster Gauge

The Webster hardness gauge (ASTM B647) (2) looks like a large pair of pliers or a paper punch. The spring-loaded head contains a conical steel indenter which is forced against the sample surface by squeezing the handles. A direct reading gauge indicates relative sample hardness on a scale of 0 to 20. This test is less precise than the Rockwell or Brinell but has the advantage of greater speed and portability. The Webster gauge was developed specifically for determination of the hardness of sheet aluminum products and its use remains largely in that industry.

3. Hardness Conversions

Despite variations in hardness test procedures and the variations in physical properties of the materials tested, hardness conversions from one test to another are possible (see ASTM E140 and Table 2). This approximate relationship is only consistent within a single-material system, eg, iron, steel, or aluminum.

Conversion of hardness data to some measure of strength is also possible and has been done for several common materials (Fig. 1). Rules of thumb have also been developed relating tensile strength to hardness for steel, eg,

$$\text{tensile strength} = \frac{\text{HBN}}{2} \times 1000$$

Caution should be exercised when using materials strength data obtained from hardness conversion tables.

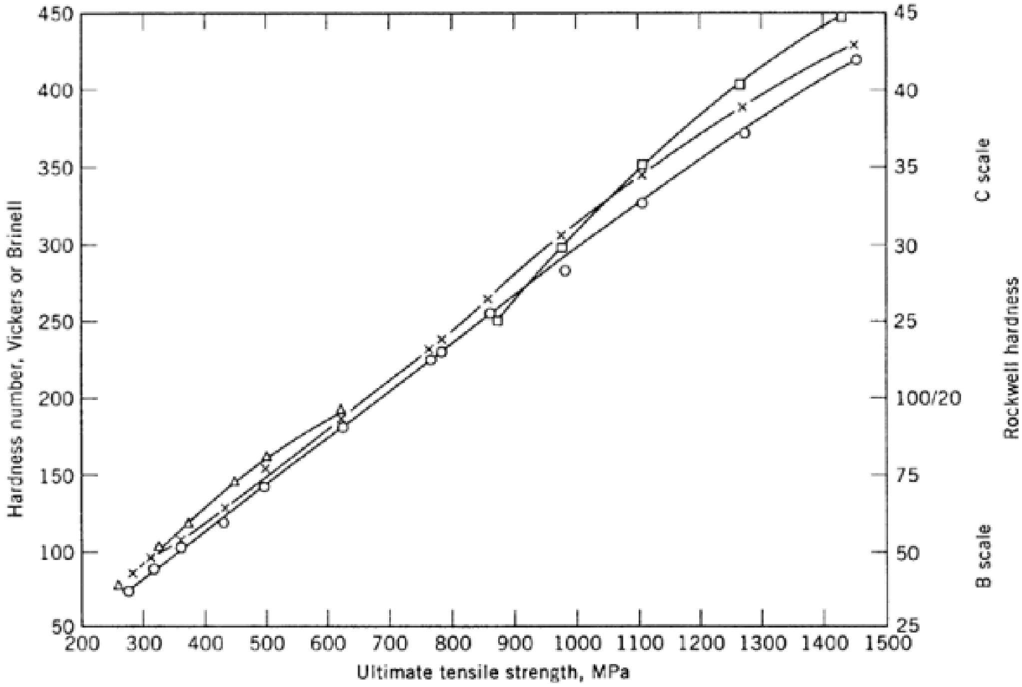

Fig. 1. Ultimate tensile strength, MPa vs hardness. Rockwell B, △; Rockwell C, □; Brinell, ○; and Vickers, ×. To convert MPa to psi, multiply by 145.

Although Vickers and DPH microhardness tests should yield the same numerical results on a given material, such is not always the case. Much of the observed variance may be a function of differences in the volume of sample material displaced by the macro and micro indentations.

Many special applications of indentation hardness testing techniques to unusual materials or conditions have been developed, some of which are listed in Table 4.

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