Hardness Test

Early Hardness Testing

Hardness, as applied to most materials, and in particular metals, is a valuable, evealing, and commonly employed mechanical test that has been in use in various orms for over 250 years. Certainly, as a material property, its value and importance cannot be understated, the information from a hardness test can complement and often be used in conjunction with other material verification techniques such as tensile or compression to provide critical performance information. How important and useful is material and hardness testing? Consider the information provided and its significance in structural, aerospace, automotive, quality control, failure analysis and many other forms of manufacturing and industry. Determining these material properties provides valuable insight to the durability, strength, flexibility, and capabilities of a variety of component types from raw materials to prepared specimens, and finished goods. Over the years, various methods for determining the hardness of materials have been developed and employed at varying levels of success. From early forms of scratch testing to sophisticated automated imaging, hardness testing has evolved into an efficient, accurate, and valued material test method.

While testing techniques and hardware has significantly improved, particularly in recent years and in step with rapidly advancing electronics, computer, hardware, and programming capabilities, earlier, basic forms of hardness testing, such as the simple scratch test, sufficed for the need of the relevant era. Some of the earliest forms of bar scratch testing date back to about 1722. These tests were based on a bar that increased in hardness from end to end. The level at which the material being tested could form a scratch on the bar was a determining factor in the specimens hardness. Later, in 1822, hardness testing forms were introduced that included scratching material surfaces with a diamond and measuring the width of the resultant line, a test eventually known as the Mohs scale. In some processes this method is still utilized today. The Mohs scale consists of ten minerals, ordered from hardest at 10 (diamond) to softest at 1 (talc). Each mineral can scratch those that fall below it in the scale hierarchy. The Mohs scale is not linear; the difference in hardness between 9 and 10 is significantly more than that between 1 and 2. To put the Mohs scale into perspective, a tangible example is that of hardened tool steel which is falls at approximately 7 or 8 on the scale. Over the next 75 years, other more refined versions of the scratch test were introduced including integrated microscope, stage, and diamond apparatuses that applied increasing loads up to 3 grams. The material to be tested was scratched under load variants and then compared to a standard set of scratches of known value. A more sophisticate version of this system employed a diamond mounted at the end of a tapered steel spring. The other end of the spring was connected to a balance arm with a 3 gram weight. The material being tested was moved by a hand actuated wheel and worm gear system, on top of which sat a stage and holding fixture for the material. A fixed pressure was applied as the material was traversed resulting in a "cut" in the material which was then measured under the microscope with the aid of filar micrometer eyepiece. A mathematical formula, inherent to the process, was then used to derive the hardness.

Later, indentation type hardness was introduced, one early form developed about 1859, was based on the load required to produce a 3.5 mm indent in the material. The depth was measured with a vernier scale system and the total load needed to reach the 3.5 mm was called the hardness. The penetrator consisted of a truncated cone that tapered from 5 mm at the top to 1.25 mm at the point. This method was mostly effective in soft materials. Another early form of indentation test involved pressing right angles geometries of the same test material into one another and measuring the width of the resulting impression. Various formats evolved from this technique during the early 1900’s that likewise used "mutual" indentation of cylindrical test material with the longitudinal axis pressed at right angles to each other.

Brinell Hardness Testing

The first widely accepted and standardized indentation-hardness test was proposed by J. A. Brinell in 1900. Brinell's interest in materials science grew during his involvement in a several Swedish iron companies and his desire to have a consistent and fast means of determining material hardness. The Brinell hardness test, still widely used today, consists of indenting the metal surface with a 1 to 10 mm diameter steel or, most recently, a tungsten carbide ball at heavy loads of up to 3,000 kg. The resultant impression, the diameter of the indentation, is measured with a low- power microscope after removal of the load. The average of two readings of the diameter of the impression at right angles are made and mathematically calculated to a hardness value. The Brinell test essentially introduced the production phase of indentation hardness testing and opened the way for additional indentation tests that were more relevant to material types.

Scleroscope Hardness Tester

Around the same time as the Brinell was developing as a useful test the Scleroscope hardness tester was introduced as one of the first "non-marking" hardness-testing instruments. Albert F. Shore, who founded the Shore Instrument Manufacturing Company in New York, and whose name is now synonymous with durometer testing, engineered the Scleroscope as an alternative hardness test. The Scleroscope used a diamond tipped "hammer", held within a glass-fronted tube that fell, from a height of 10 inches, onto a test specimen. The rebound of the hammer was measured on a graduated scale of "Shore" units, each divided into 100 parts that provide a comparison with the rebound that might be expected from hardened high-carbon steel. The hardness reading is technically a measure of the material's elasticity. One significant advantage of the Scleroscope was its' "non-destructive" nature in that, unlike the other available methods of hardness testing at the time, a Scleroscope left only a slight mark on the material under test making, presumably leaving it available for use after evaluation. As the 20th century progressed and endured two world wars, with the simultaneous blossoming of the industrial revolution, increased manufacturing requirements and global industrialization brought an urgent demand for more refined and efficient test methods and new techniques began to develop. Accurate, efficient forms of testing were needed in reaction to heavy manufacturing demands, structural failures, and the need to design sufficient material integrity into the growing global infrastructure.

Vickers Hardness Testing

As an alternative to the Brinell, the Vickers hardness test was developed in 1924 by two gentlemen, Smith and Sandland, at Vickers Ltd, a British Engineering conglomerate. The test was designed in reaction to the need to have a more refined test over the material limitations that the Brinell was effective on. The Vickers test uses the same principle as the Brinell, that of a regulated impression on the material, but instead utilized a pyramid shaped diamond rather than the Brinell ball indenter. This resulted in a more consistent and versatile hardness test. Later, in 1939, an alternative to the Vickers test was introduced by Fredrick Knoop at the US National Bureau of Standards. The Knoop test utilized a shallower, elongated format of the diamond pyramid and was designed for use under lower test forces than the Vickers hardness test, allowing for more accurate testing of brittle or thin materials. Both the Vickers and Knoop tests continue as popular hardness analysis methods today.

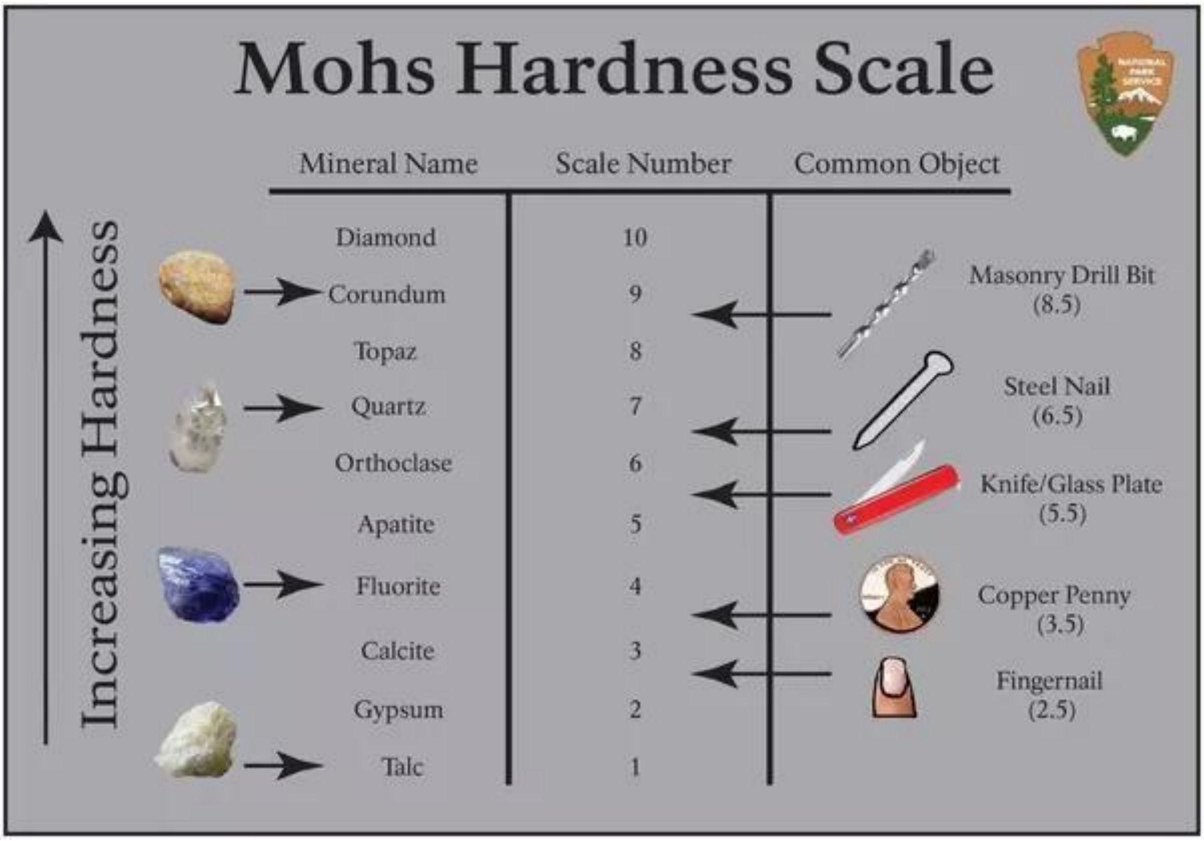
Rockwell Hardness Testing

Although conceived as an idea in 1908 by a Viennese professor, Paul Ludwik, the Rockwell indentation test did not become of commercial importance until around 1914 when brothers Stanley and Hugh Rockwell, working from a manufacturing company in Bristol Connecticut, expanded upon the idea of utilizing a conical diamond indention test based on displacement and applied for a patent for a Rockwell tester design. The principal criterion for this tester was to provide a quick method for determining the effects of heat treatment on steel bearing races. One of the main strengths of the Rockwell was the small area of indentation needed. It is also much easier to use as readings are direct, without the need for calculations or secondary measurements. The patent application was approved on February 11, 1919 and later, in 1924 a more an improved design patent was granted. Simultaneously, Stanley Rockwell was starting commercial production of Rockwell testers in collaboration with instrument manufacturer Charles H. Wilson in Hartford, Connecticut. The company grew into the Wilson Mechanical Instrument Company and became known as the premium producer of Rockwell testers. After some ownership changes through the latter 1900's, Wilson was acquired in 1993 by Instron, a worldwide leader in the material testing industry and today has become an integral part of Instron/Illinois Tool Works. Now known as Wilson Hardness, the combined expertise of Instron/Wilson, coupled with the subsequent acquisitions of Wolpert Hardness and Reicherter Hardness, have led to the engineering and production of cutting edge hardness systems. The Rockwell test remains as one of the most efficient and widely used hardness test types in use.

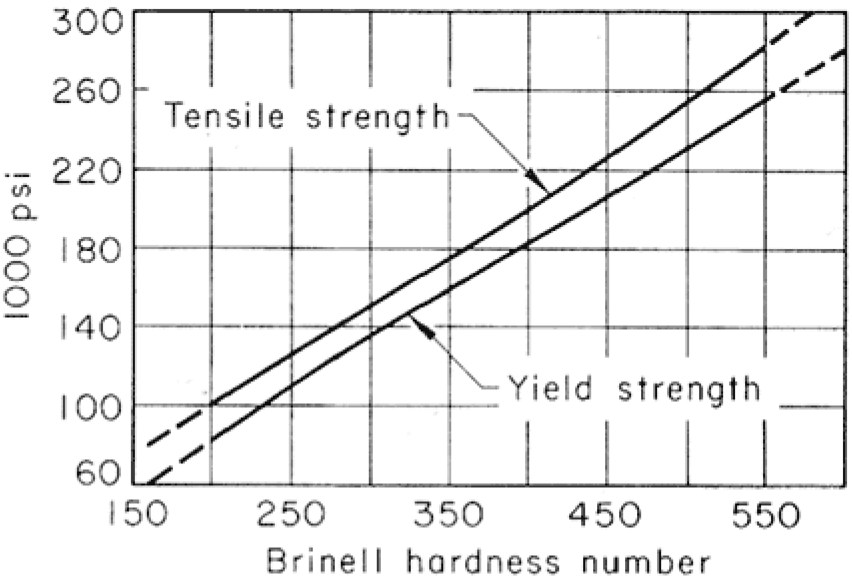
Hardness Testing- Today and the Future

Now, with significant improvements in recent years in hardness testing instrumentation, computer hardware, electronics, imaging algorithms, and software capabilities the door has opened to extremely precise and reliable testing processes that provide results more quickly than ever before, often in automated fashion. These components and techniques have proven to be beneficial in raising efficiency, speed, and accuracy to unparalleled levels. Over the past several years and no doubt increasingly in the future, more traditional manual test processes have and will continue to rapidly give way to automation in every aspect of the testing process. New techniques in material preparation and handling, mount fixturing, stage movement, results interpretation, and analysis, and even reporting have now been introduced to the hardness testing industry. More and more automation technology is being integrated into many hardness systems using stage traversing and image analysis of Knoop, Vickers, and Brinell indentations. An automatic hardness system typically consists of a fully controllable tester, including an auto-rotating or revolving turret as well as actuation in the Z axis either from the head/indenter housing or from a spindle driven system used for both applying the indent at a predetermined force as well as for automatically focusing the specimen. Add to this a standard computer with dedicated hardness software, an automatic XY traversing motorized stage, and a USB video camera, and the result is a powerful, fully automatic hardness testing system. These systems can be left alone to automatically create, measure, and report on an almost unlimited number of indentation traverses. This newer technology eliminates much of the hardware that in the past caused operational challenges and cluttered workspace. Hardness testing plays an important role in materials testing, quality control, and acceptance of components. We depend on the data to verify the heat treatment, structural integrity, and quality of components to determine if a material has the properties necessary for its intended use. Through the years, establishing means of increasingly more productive and effective testing through refining traditional testing design has given way to new cutting edge methods that perform and interpret hardness tests more effectively than ever before. The result is increased ability and dependence on "letting the instrument do the work," contributing to substantial increases in throughput and consistency and continuing to making hardness tests very useful in industrial and R&D applications and in insuring that the materials utilized in the things we use every day contribute to a well-engineered, efficient, and safe world.

Hardness is a measure of the material's resistance to localized plastic deformation (e.g. dent or scratch)



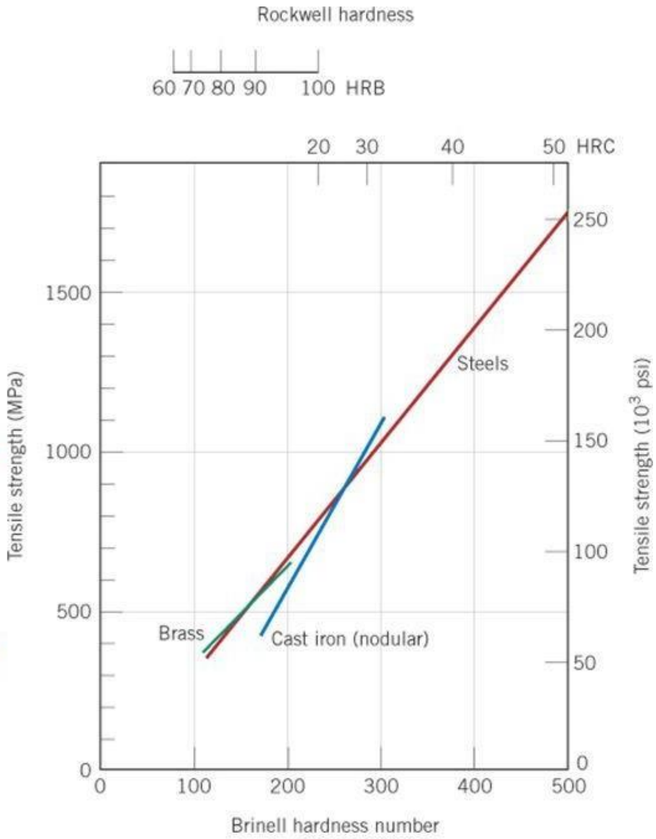
A qualitative Moh's scale, determined by the ability of a material to scratch another material: from 1 (softest = talc) to 10 (hardest = diamond).

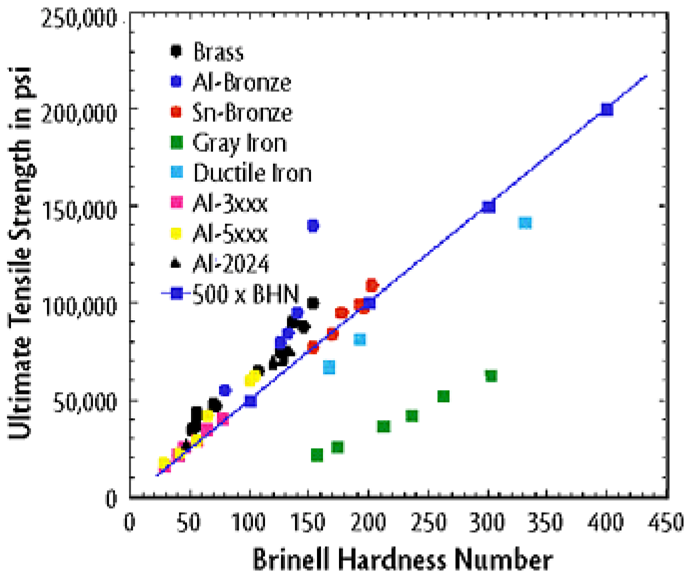


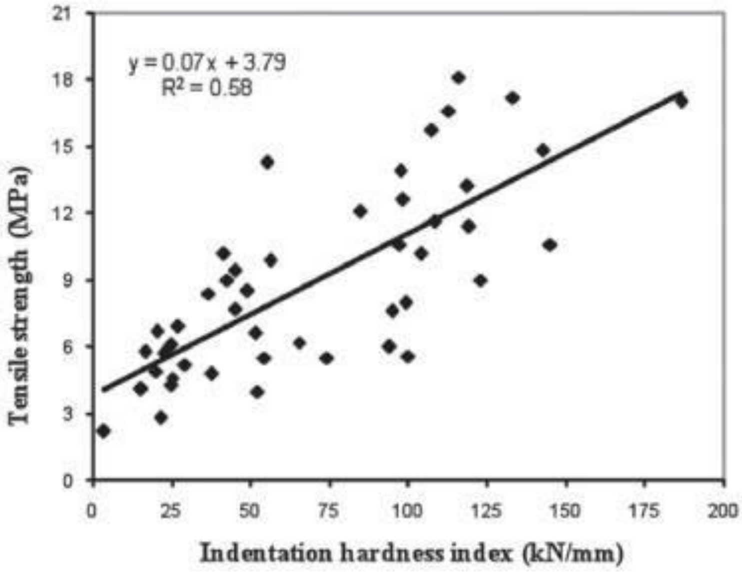
Correlation between Hardness and Tensile Strength

- Both hardness and tensile strength are indicators of a metal's resistance to plastic deformation.
- For cast iron, steel and brass, the two are roughly proportional.

- Tensile strength (psi) = 500*BHR




Ultimate Tensile Strength in psi
250,000
200,000
150,000
100,000
50,000
0
Brass
Al-Bronze
Sn-Bronze
Gray Iron
Ductile Iron
Al-3xxx
Al-5xxx
Al-2024
500 x BHN
0 50 100 150 200 250 300 350 400 450
Brinell Hardness Number


y = 0.07x + 3.79
R² = 0.58
Tensile strength (MPa)
21 18 15 12 9 6 3 0
0 25 50 75 100 125 150 175 200
Indentation hardness index (kN/mm)

HARDNESS TEST

1. OBJECT

The hardness test is a mechanical test for material properties which are used in engineering design, analysis of structures, and materials development. The principal purpose of the hardness test is to determine the suitability of a material for a given application, or the particular treatment to which the material has been subjected. The ease with which the hardness test can be made has made it the most common method of inspection for metals and alloys.

1. INTRODUCTION

Hardness is defined as the resistance of a material to permanent deformation such as indentation, wear, abrassion, scratch. Principally, the importance of hardness testing has to do with the relationship between hardness and other properties of material. For example, both the hardness test and the tensile test measure the resistance of a metal to plastic flow, and results of these tests may closely parallel each other. The hardness test is preferred because it is simple, easy, and relatively nondestructive.

There are many hardness tests currently in use. The neccessity for all these different hardness tests is due to the need for categorizing the great range of hardness from soft rubber to hard ceramics.

3. THEORY

Current practice divides hardness testing into two categories: macrohardness and microhardness. Macrohardness refers to testing with applied loads on the indenter of more than 1 kg and covers, for example, the testing of tools, dies, and sheet material in the heavier gages. In microhardness testing, applied loads are 1 kg and below, and material being tested is very thin (down to 0.0125 mm, or 0.0005 in.). Applications include extremely small parts, thin superficially hardened parts, plated surfaces, and individual constituents of materials.

1) Macro Hardness Testers Loads > 1 kg

- Rockwell
- Brinell
- Vickers

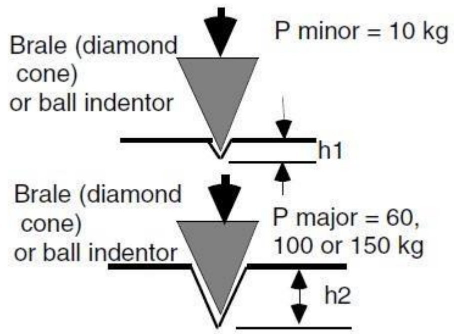
2) Micro Hardness Testers < 1 kg

- Knoop diamond
- Vickers diamond pyramid

Macro Hardness Test Methods

Rockwell Hardness Test

The Rockwell hardness test method consists of indenting the test material with a diamond cone or hardened steel ball indenter. The indenter is forced into the test material under a preliminary minor load $_0$ (Fig. 1A) usually 10 kgf. When equilibrium has been reached, an indicating device, which follows the movements of the indenter and so responds to changes in depth of penetration of the indenter is set to a datum position. While the preliminary minor load is still applied an additional major load is applied with resulting increase in penetration (Fig. 1B). When equilibrium has again been reach, the additional major load is removed but the preliminary minor load is still maintained. Removal of the additional major load allows a partial recovery, so reducing the depth of penetration (Fig. 1C). The permanent increase in depth of penetration, resulting from the application and removal of the additional major load is used to calculate the Rockwell hardness number.



Rockwell Scale (X =)	Indentor	Pmajor (kg)
A	Brale (diamond)	60
B	1/16" ball	100
C	Brale (diamond)	150
D	Brale (diamond)	100
E	1/8" ball	100
F	1/8" ball	60
M	1/4" ball	100
R	1/2" ball	60

$$HRX = R_X = M - \frac{(h_2 - h_1)}{0.002}$$

M = 100 for A, C, and D scales

M = 130 for B, E, M, R, etc. scales

Figure 1. Rockwell Principle

There are several considerations for Rockwell hardness test

- Require clean and well positioned indenter and anvil

- The test sample should be clean, dry, smooth and oxide-free surface

- The surface should be flat and perpendicular to the indenter

- Low reading of hardness value might be expected in cylindrical surfaces
- Specimen thickness should be 10 times higher than the depth of the indenter
- The spacing between the indentations should be 3 to 5 times of the indentation diameter
- Loading speed should be standardized.

The Brinell Hardness Test

The Brinell hardness test method consists of indenting the test material with a 10 mm diameter hardened steel or carbide ball subjected to a load of 3000 kg. For softer materials the load can be reduced to 1500 kg or 500 kg to avoid excessive indentation. The full load is normally applied for 10 to 15 seconds in the case of iron and steel and for at least 30 seconds in the case of other metals. The diameter of the indentation left in the test material is measured with a low powered microscope. The Brinell harness number is calculated by dividing the load applied by the surface area of the indentation. When the indentor is retracted two diameters of the impression, d_1 and d_2 , are measured using a microscope with a calibrated graticule and then averaged as shown in *Fig.2(b)*.

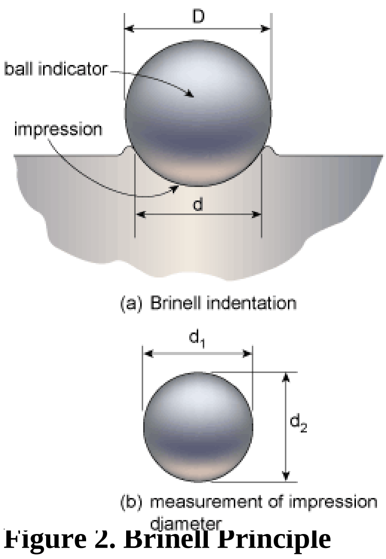


Figure 2. Brinell Principle

$$BHN = \frac{P}{\frac{\pi D}{2}\left[D - \sqrt{D^2 - d^2}\right]}$$

Where:

P is the test load [kg]

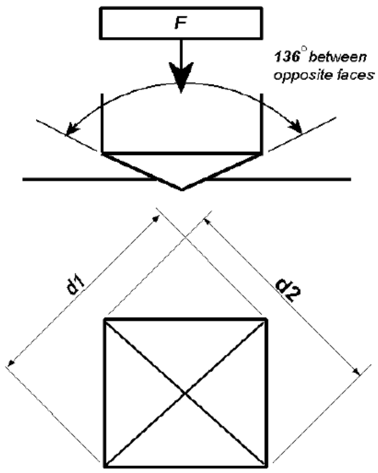
D is the diameter of the ball [mm]

d is the average impression diameter of indentation [mm]

The diameter of the impression is the average of two readings at right angles and the use of a Brinell hardness number table can simplify the determination of the Brinell hardness. A well structured Brinell hardness number reveals the test conditions, and looks like this, "75 HB 10/500/30" which means that a Brinell Hardness of 75 was obtained using a 10mm diameter hardened steel with a 500 kilogram load applied for a period of 30 seconds. On tests of extremely hard metals a tungsten carbide ball is substituted for the steel ball. Compared to the other hardness test methods, the Brinell ball makes the deepest and widest indentation, so the test averages the hardness over a wider amount of material, which will more accurately account for multiple grain structures and any irregularities in the uniformity of the material. This method is the best for achieving the bulk or macro-hardness of a material, particularly those materials with heterogeneous structures.

Vickers Hardness Test

The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a load of 1 to 100 kgf. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The Vickers hardness is the
quotient obtained by dividing the kgf load by the square mm area of indentation.



$$HV = \frac{2F\sin\frac{136^{\circ}}{2}}{d^2} \qquad HV = 1.854\frac{F}{d^2} \text{ approximately}$$

F= Load in kgf

d = Arithmetic mean of the two diagonals, *d1* and *d2* in mm

HV = Vickers hardness

Figure 3. Vickers Principle

When the mean diagonal of the indentation has been determined the Vickers hardness may be calculated from the formula, but is more convenient to use conversion tables. The Vickers hardness should be reported like 800 HV/10, which means a Vickers hardness of 800, was obtained using a 10 kgf force. Several different loading settings give practically identical hardness numbers on uniform material, which is much better than the arbitrary changing of scale with the other hardness testing methods. The advantages of the Vickers hardness test are that extremely accurate readings can be taken, and just one type of indenter is used for all types of metals and surface treatments. Although thoroughly adaptable and very precise for testing the softest and hardest of materials, under varying loads, the Vickers machine is a floor standing unit that is more expensive than the Brinell or Rockwell machines.

Hardness testing in estimating other material properties:

Hardness testing has always appeared attractive as a means of estimating other mechanical properties of metals. There is an empirical relation between those properties for most steels as follows:

UTS = 0.35**BHN* (in kg/mm2)

This equation is used to predict tensile strength of steels by means of hardness measurement. A reasonable prediction of ultimate tensile strength may also be obtained using the relation:

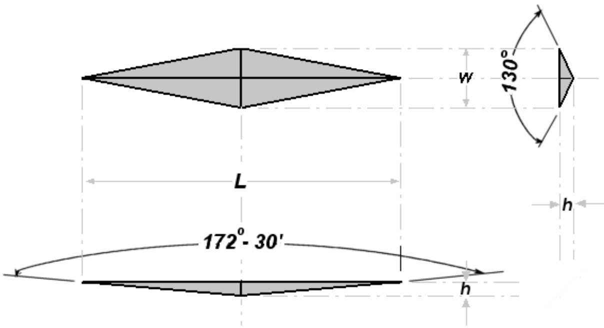
$$UTS = \frac{VHN}{3}\left[1-(n-2)\right]\left\{\frac{12.5(n-2)}{1-(n-2)}\right\}^{(n-2)}$$

where VHN is the Vickers Hardness number and n is the Meyer's index.
The 0.2 percent offset yield strength can be determined with good precision from Vickers hardness number according to the relation: *(Hint: For steels, the yield strength can generally be taken as 80% of the UTS as an approximation)*

$$YS_{0.2} = \frac{VHN}{3}(0.1)^{(n-2)}$$

3.2 Micro Hardness Test Methods

The term microhardness test usually refers to static indentations made with loads not exceeding 1 kgf. The indenter is either the Vickers diamond pyramid or the Knoop elongated diamond pyramid. The procedure for testing is very similar to that of the standard Vickers hardness test, except that it is done on a microscopic scale with higher precision instruments. The surface being tested generally requires a metallographic finish; the smaller the load used, the higher the surface finish required.



Knoop Hardness Indenter Indentation

The Knoop hardness number KHN is the ratio of the load applied to the indenter, P (kgf) to the unrecovered projected area A (mm^2).

KHN = F/A = P/CL^2

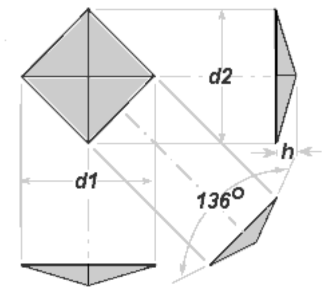
Where:

F=applied load in kgf

A=the unrecovered projected area of the indentation in mm^2

L=measured length of long diagonal of indentation in mm

C = 0.07028 = Constant of indenter relating projected area of the indentation to the square of the length of the long diagonal.



Vickers Pyramid Diamond Indenter Indentation

The Vickers Diamond Pyramid hardness number is the applied load (kgf) divided by the surface area of the indentation (mm^2)

$$HV = \frac{2F\sin\frac{136^o}{2}}{d^2} \qquad HV = 1.854\frac{F}{d^2} \text{ approximately}$$

Where:

F= Load in kgf

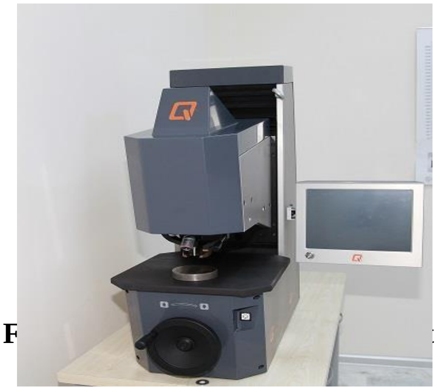
d = Arithmetic mean of the two diagonals, *d1* and *d2* in mm

HV = Vickers hardness

Comparing the indentations made with Knoop and Vickers Diamond Pyramid indenters for a given load and test material:

- Vickers indenter penetrates about twice as deep as Knoop indenter
- Vickers indentation diagonal about 1/3 of the length of Knoop major diagonal
- Vickers test is less sensitive to surface conditions than Knoop test
- Vickers test is more sensitive to measurement errors than knoop test
- Vickers test best for small rounded areas
- Knoop test best for small elongated areas
- Knoop test good for very hard brittle materials and very thin sections

4. EXPERIMENTS



Selected samples will be selected to be tested by Brinell, Vickers and Rockwell hardness test, the results are given to students in the class lab by the *Qness* hardness test machine in Fig. 4. Different materials specimens will be tested in this laboratory experiment namely: aluminum alloy, carbon steel, brass, commercial pure copper, brass, and stainless steel etc.

F

Results

Samples will be selected to be tested by Brinell, Vickers and Rockwell hardness test, the results are given to students in the class lab.

a) For Brinell experiment, student has to calculate the BHN and depth of impression (***h)*** through the following formulas for each material tested:

$$BHN = \frac{P}{\frac{\pi D}{2}\left[D-\sqrt{D^2-d^2}\right]} \qquad h = \frac{1}{2}\left[D-\sqrt{D^2-d^2}\right] \; or \; h = \frac{P}{\pi D \times BHN}$$

In the class, the values of *P* and *d* (*d* and *d*) hane been given to students.

b) For Vickers experiment, student has to calculate the VHN through the following formula for each material tested:

$$VHN = \frac{2\,P\,\sin\frac{136}{2}}{d^2}$$

In the class, the values of P and d ($_1$ and $_2$) had been given to students.

c) For Rockwell experiment, student has to calculate the depth (h_2-h_1) due to the major load through the following formulas for each used indenter:

$$HRX = R_X = M - \frac{(h_2 - h_1)}{0.002}$$

M = 100 for A, C, and D scales

M = 130 for B, E, M, R, etc. scales

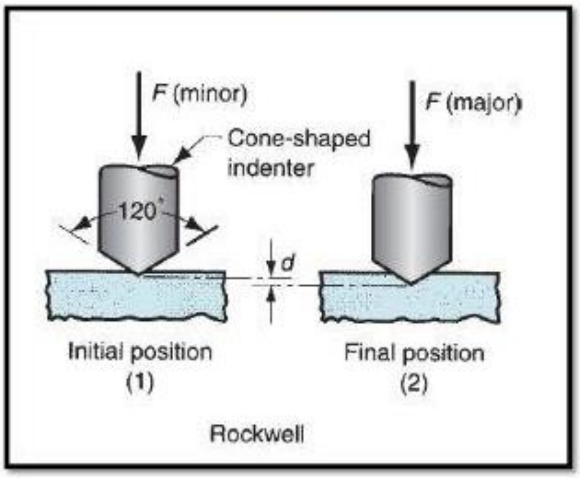
d) Which factors effect the selecting of the appropirate hardness test?

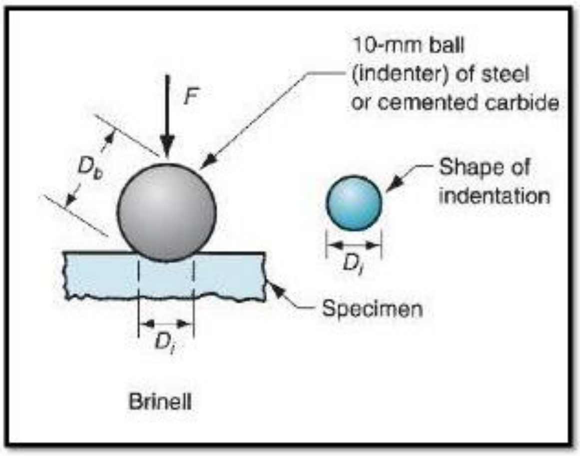
e) Discuss the advantages and disadvantages of the Brinell, Vickers and Rockwell Hardness Tests.

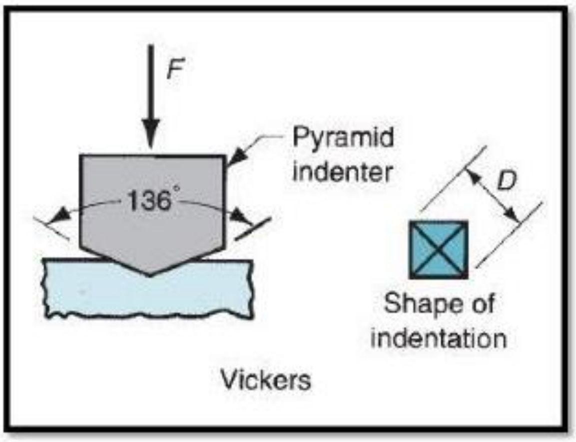
f) Discuss the relationship between hardness and tensile properties.

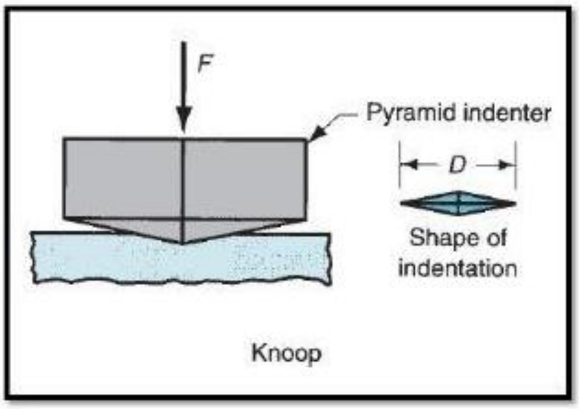
Rockwell	**Brinell**	**Vickers**	**Knoop**
No specimen preparation required	The specimen surface can be rough	Specimens need to be prepared	Can be used with any and all materials and test specimens
Hardness value directly readable, no optical evaluation required	Good illumination of the test indent is important for ensuring correct evaluation of the test indent (e.g. with the aid of a ring light).	Due to the need to conduct optical indent evaluation, Vickers hardness testers must be equipped with an optical system	Evaluation is more precise than the Vickers method, Must be equipped with an optical system
Quick & cost-effective process	The process is slow (by comparison with the Rockwell method). The test cycle takes somewhere between 30 and 60 seconds	The process is rather slow. The test cycle takes somewhere between 30 and 60 seconds	The process is rather slow (compared with the Rockwell method). The test cycle takes somewhere between 30 and 60 seconds
Non-destructive testing	Limitation in applying the method on thin specimens of very hard materials	Non-destructive testing is possible	The test is non-destructive
Not always the most accurate hardness testing method	High risk of deforming the material to be tested when testing in the macro range with high test loads	More expensive to purchase than Rockwell testers due to optical system	More expensive to purchase than Rockwell testers
The test location must be completely free of all contamination (e.g. scale, foreign bodies or oil)	The surface quality of the specimen must be good, because the indent is measured optically	The surface quality of the specimen must be good (ground and polished)	The surface quality of the specimen must be good, because the indent is measured optically
The indenter has unknown effects on the test results	Relatively large test indents that are easier to measure the rather small Vickers indentations	Only one type of indenter	There is only one type of indenter
With increasing hardness, it becomes increasingly difficult to distinguish between materials	Can be used for testing non-homogeneous materials (e.g. castings)	The Vickers method can be used with any and all materials and test specimens	It is particularly suitable for testing small, longish components and very thin layers as well as brittle materials (glass and ceramics) for which no other method is appropriate.

Test	Indenter	Shape of indentation: Side view	Shape of indentation: Top view	Load, P	Hardness number
Brinell	10-mm steel or tungsten-carbide ball	D, d	d	500 kg 1500 kg 3000 kg	$HB = \frac{2P}{(\pi D)(D - \sqrt{D^2 - d^2})}$
Vickers	Diamond pyramid	136°	L	1–120 kg	$HV = \frac{1.854P}{L^2}$
Knoop	Diamond pyramid	$L/b = 7.11$ $b/t = 4.00$ t	b, L	25 g–5 kg	$HK = \frac{14.2P}{L^2}$
Rockwell A, C, D	Diamond cone	120° t = mm		60 kg 150 kg 100 kg	HRA, HRC, HRD $= 100 - 500t$
B, F, G	$\frac{1}{16}$-in. diameter steel ball	t = mm		100 kg 60 kg 150 kg	HRB, HRF, HRG $= 130 - 500t$
E	$\frac{1}{8}$-in. diameter steel ball			100 kg	HRE $= 130 - 500t$









5. REPORT

In your laboratory reports must have the followings;

a) Cover

b) A short introduction

c) All the necessary calculations using measured data.

d) Discussion of your results and a conclusion.

References

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