PRACTICAL

HARDNESS TESTING

MADE SIMPLE

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1. GENERAL

Important facts and features to be known and remembered.

This book intends to stress the significance of Hardness Testing and to dispel a few common misconceptions attributing to it inappropriate meanings and implications.

It is dedicated to all people using Hardness Testing in their daily work, for them to be aware of the usefulness of the methods, when applied correctly, and of the dangers of faulty generalizations, if interpreted outside the frame of their relevance.

It may also be useful for students learning to practice Hardness Testing, to orient them in the understanding of a broader meaning of the results collected.

The information appearing in the following pages can be found in the best Handbooks dealing with the subject matter. As these may or may not be readily available to the interested persons, the material included is presented here following the personal experience and preference of the writer.

Note: the information, given herewith in good faith for enlarging the understanding of quite common a testing, is believed to be correct at the time of this writing, fruit of longtime practice with actual operations in an industrial environment.

Nothing written here though should be construed as authority to use the results for reaching conclusions bearing direct influence on possible harming of people or loss of material gain.

Users do so at their own entire risk. No responsibility is accepted for any action taken or withheld as a consequence of the information submitted here.

2. INTRODUCTION

For **Metallurgists**, Hardness Testing is a collection of different methods for measuring a definite characteristic of metallic materials, namely:

a) the resistance to penetration of a specific Indenter (defined by fixed form and properties),

b) under the application of a certain static force,

c) for a definite time,

d) using precise measuring procedures.

The result, usually expressed by a number or by a range of numbers, must be qualified by an accepted convention indicating exactly by which one of the possible methods such result was obtained.

Hardness so defined is not an intrinsic property of any material, (like density or melting point), it is rather a characteristic deriving from the composition, the thermal and mechanical history of the material, and essentially from the structure (or more properly the microstructure) of the specimen involved.

The variety of methods and conditions developed for hardness testing is a consequence of the fact that no single method can cover all the possible degrees of this characteristic.

All the methods employed are empirical, in the sense that they were developed by trial and error to satisfy a need, and that they knew their enormous diffusion due to their intrinsic usefulness.

It is commonly believed that, for practical purposes, in a definitely limited range, there is an approximate correspondence between hardness data and a range of tensile strength results.

While this assumption is generally correct if taken with due caution, one must remember that no indication regarding ductility is obtained through hardness testing.

The long practice of application of different methods of testing has produced a wealth of data which has permitted the comparison of values obtained on the same specimen.

ASTM E 140, Standard Hardness Conversion Tables for Metals, (for information on where to find, see at the end of this publication) is the best known and authoritative such compilation.

Caution however should be applied when intending to use the comparison, making sure that it is valid for the material in question, (hard steel, soft steel, nickel alloys, magnesium alloys, brass, aluminum alloys) and keeping in mind that in any case it is only an approximation.

To specialists in different disciplines, hardness may have different meanings, which should not concern us here, except for a very common misconception, generally believed by people involved in machining using metal removal by a cutting tool, where hardness is held as an indication of the ease or difficulty of chip removal. In certain cases it is not so.

Examples:

1) - Extremely difficult to machine materials, like austenitic stainless steels or heat resistant alloys, have quite normal medium range hardness values, which give no hint to the elevated forces involved in the process of deforming and tearing chips out of the surface.

2) - On the other hand free machining stainless steels, where appropriate materials like Sulfur or Selenium were added to their composition in order to break up the chips, present the same medium range hardness, without revealing their most important characteristic.

Hardness Testing, as defined above,

- is inexpensive,
- non destructive,
- easy to implement with properly calibrated equipment,
- by operators who can easily be trained and supervised,
- applying understandable written procedures strictly maintained,
- and gives useful information if it is known what it represents.

In particular it is a very useful tool for process control and for materials acceptance, if performed correctly. Therefore, and this is the danger, it is often taken for granted with no further consideration.

However one must always keep in mind that the test is localized, that it is true only on the spot where it was determined. One cannot assume that it is valid for all the volume unless one can be sure that the material is homogeneous (the same everywhere) and that the mechanical and thermal processes produced uniform results. This is the most usual cause of erroneous conclusions derived while overlooking the origins of unaccounted for behavior.

Therefore hardness readings will NOT represent true through hardness when:

- plating by a different material (e.g. chromium) is present
- a plasma or thermally sprayed layer was deposited
- the specimen is decarburized (having lost carbon) on the surface
- case hardening was performed (carburizing, induction or flame hardening, nitriding etc.)
- welding or flame cutting was done nearby
- a recast layer, produced by electrodischarge machining, is present
- local strain (deformation) hardening like disc cutting took place on the tested surface
- surface improvement process like shot peening is present
- the part has widely varying (thick and thin) sections where response to heat treatment may be different
- the surface was abusively treated (e.g. by uncontrolled grinding) producing local overheating
- there is reason to suspect that hardness is not constant through the thickness of part.

Furthermore an erroneous hardness reading can easily be obtained if the correct rules of application of the specific method involved are not implemented.

Therefore one should always check if the method selected is appropriate for the results sought for and if the test was applied correctly by a knowledgeable operator, with properly maintained and calibrated equipment.

The complete Calibration of a Hardness Testing machine, which should be performed at least annually, consists in the direct verification of each of its important features, including the actual value of the applied force using calibrated load cells or other specialized instruments.

During normal operation one must perform, as required by Recommended Practices, a daily hardness check on a Reference Block of known hardness. This is an indirect verification, to ensure that the testing machine provides the correct result reported for the Block.

Reference Blocks, also known as Hardness Test Blocks, are manufactured to have the most homogeneous hardness on all of their surface, and their nominal hardness was determined with utmost care at the origin. Any deviation from the standard result requires a thorough overhaul and systematic check and calibration of the machine.

Reference Blocks should be treated as most precious accessories for controlling the quality of routine hardness testing: as such they must be obtained from reputable sources with a signed Certificate.

Hardness Reference Blocks:

- Must be kept clean in an environment where they will not rust
- and will not be exposed to excessive heat (which could change their properties)
- They must be used only on their polished face (never on the opposite one)
- The impressions must be far from edges and from one another (at least three times their size)
- No attempt should be made to reclaim them by grinding

In the following only the most important testing methods along with their rules shall be recalled and explained. Other methods exist, each one with its particular niche of applicability and usefulness, but on purpose we leave them out of this exposition.

3. BRINELL HARDNESS TEST.

One of the most popular hardness testing methods, Brinell Hardness Number is obtained using a perfectly spherical hardened steel ball of 10 mm diameter pressed against the test surface using a static force of 3000 kg (=29.42 kiloNewton) for at least 10 seconds for steel and measuring the diameters of the indentation left on the surface by means of a graduated low power microscope. The result is either calculated using a given formula (see at the end of this section) or looked up on prepared Tables.

The equipment generally consists of a manually operated hydraulic press holding the test piece on a sturdy table and forcing a properly held ball indenter into the surface while avoiding impact.

Simple as it looks, it is a precise testing method giving repeatable and meaningful results but only when applied correctly.

The theory and practice of the method are presented in the most complete way in the current Standard:

ASTM E 10, Standard Test Method for Brinell Hardness of Metallic Materials.

This Standard is prepared and maintained by the American Society for Testing and Materials.

An International Standard, issued by ISO - International Standards Organisation, available on this subject is:
ISO 6506-1 Metallic Materials - Brinell Hardness Test. Part 1 - Test Method

Note: Links to the Sources ASTM and ISO can be found at the end of this Publication.

The importance of learning and understanding Standards requirements cannot be overemphasized.

It is also strongly recommended to study with attention the Operating Manual of the equipment on hand and to take care of maintenance operations as advised by the manufacturer.

Brinell Hardness Test is most often applied on iron and steel castings where its usefulness is most advantageous as the results represents a sort of average surface hardness because these materials are not uniform on the microscopic scale.

It can also be successfully applied to steel bars and plates, and to normalized forgings, that is to forgings which were submitted to a homogenizing heat treatment, or to fully heat treated ones.

Assuming that the surface is representative of sound metal, for ease of reading the indentation diameters one should have it cleaned from paint, oil or grease, and lightly ground with abrasive paper (180 grit).

The results obtained, even when the test was performed with utmost care, could be wrong:

- if the surface is not flat
- if the surface is covered with a thick scale
- if the tested material is too thin (less than 9.6 mm or 3/8 ") so that a mark appears on the opposite side
- if the tested material is too hard (more than 450 HBS for steel ball or more than 650 HBW for tungsten carbide ball).

The letters HBS stand for Hardness Brinell with steel ball, (HBW for tungsten carbide ball) but the qualification should be completed by indicating also the ball diameter (10 mm) and the applied force (load) (3000 kg).

The complete and meaningful designation is therefore expressed as:
450 HBS10/3000 or 450 $HBS_{10/3000}$.

Note: ASTM Standardization News of February 2000 announces that sometime in the future a change will take place, whereby steel balls for indenters will be substituted by tungsten carbide balls for all the ranges, in a movement that will align ASTM E 10 with ISO 6506.

In general one should not attempt to establish a Brinell Hardness Number if the diameter of the indentation is smaller than 2.4 mm (24%) or larger than 6 mm (60% of a 10 mm diameter ball).

One of the most useful features of Brinell Hardness Test derives from the observation that if the ratio of Force F (in kg) to the square of Ball Diameter D (in mm) is kept constant, one

obtains an approximation of the same BHN (Brinell Hardness Number) as measured with the standard parameters (10 mm ball and 3000 kg).

Therefore, with available equipment of special design, one can use the method with the following pairs of Force and Ball Diameter for $F/D^2 = 30$:

Force (kg)	3000	750	187.5	30
Ball Diameter(mm)	10	5	2.5	1

The application of these different parameters enlarges the scope of the method for thinner or more delicate machine elements.

Until now applications were described for ferrous metals.

But the usability is extended to softer materials like copper or aluminum alloys at the condition of establishing a different ratio for F/D^2 like 15, 5, 2.5, 1.25, 1.

It is evident that, to be understood, the test so performed MUST be qualified with the indication of force and of ball diameter.

According to the above mentioned ASTM Standard E 10 the following ratios should be used for the materials indicated:

For hard copper and aluminum alloys : $F/D^2 = 15$
For soft copper and aluminum alloys : $F/D^2 = 5$

For lead and soft alloys: any one of the smaller values.

Although most of Brinell testing is performed with machines firmly standing on the floor, there are a few portable instruments which have proven their usefulness, permitting to take the test to very large and heavy raw metal parts.

This type of portable instrument performs the regular test and the results are therefore perfectly acceptable as if they were obtained with the original equipment.

Other instruments though are based upon different physical principles and show a translation of the value using some correspondence table which at best is approximate: one should always beware of optimistic affirmations of manufacturers because translated results from different instruments are generally not accepted as an alternative fulfillment of contract requirement.

The formula used for calculating Brinell Hardness Number is as follows:

BHN = $P/\ \pi * D/2 *(D\text{-}SQRT(D^2 - d^2))$ where:

P = test load in kilograms, D = diameter of ball in mm

d = diameter of read impression in millimeters (or average of two readings, mutually perpendicular)

SQRT, / and * = Square Root, division and multiplication symbols.

4. VICKERS HARDNESS TEST

Vickers Hardness is a very popular test, which is characterized by a square based diamond pyramid indenter, exactly ground to a standard form with 136 degrees between opposite faces and used to leave a mark in metal under a precisely applied force by taking care to avoid impact: the diagonals of the impression have to be measured using a suitable microscope and the results are either calculated using a given formula (see at the end of this section) or looked up in Tables arranged for each of the forces (loads) used.

The theory and practice of the test is most authoritatively exposed in:
ASTM E 92 - Standard test method for Vickers Hardness of Metallic Materials

An International Standard, issued by ISO - International Standards Organization, available on this subject is:
ISO 6507-1 Metallic Materials - Vickers Hardness Test. Part 1 - Test Method

Note: for information on where to find, see at the end of this Publication.

The importance of learning and understanding Standards requirements cannot be overemphasized.

The values found are designated by HV for Hardness Vickers, followed by the force (load) in kg, or by DPH which means Diamond Pyramid Hardness and sometimes with the number of seconds when the load was applied.

Commonly used loads are 5, 10, 30 and 50 kg, but the range can be enlarged if necessary. In theory the hardness number should be independent of the force used, but in practice, as differences can be found, one must always report the load used.

It is therefore similar to the Brinell test, but although overlapping, the typical applications are different: therefore Vickers should not be used for cast iron which has a non uniform structure, because the impression tends to be small, and unable to give a true average. The smaller impression requires a smoother surface, to be read accurately.

Vickers hardness is applicable to soft and hard materials, to thick and thin specimens. There is no danger to deform the indenter during normal operation, but sharp blows must be avoided because the diamond tip could break and then give erroneous results.

Minimum thickness of at least ten times the depth of the indentation is to be observed, but it is easier to reduce it, simply by selecting a lighter load. As usual no marks should be seen on the opposite surface.

Many different types of Vickers hardness testers exist, from different manufacturers. As with any precision instrument, the equipment should be regularly maintained following the instructions, and the tip of the pyramid should be examined under a microscope at regular time intervals.

For completeness we shall note that for testing very thin specimens or layers, (or even single crystals or phases in a microstructure) a similar method has been standardized which employs very light forces (loads) (from 1 g to 1 kg).

The theory and practice of this test can be found in:
ASTM E 384 - Standard Test Method for Microhardness of Materials

Note: Sometimes this test is called Microindentation Hardness.

It should be understood that these microhardness values cannot be interchanged with regular Vickers Hardness values and that they do not represent bulk hardness of sizeable chunks of materials.

The formula used for calculating the Vickers Hardness Number (or Diamond Pyramid Hardness) is:

$$HV_P = 1.8544 * P/ d^2$$

where:

P = force (load) in kilograms

d = diagonal length of the impression in mm millimeters (or, better, average of two readings, mutually perpendicular).

5. ROCKWELL HARDNESS TESTING

Rockwell Hardness is probably the most used hardness testing method because it is simple and self contained, so that there is no need for a separate microscope reading. And its values have a lot of meaning for practicing mechanics. However, being so sensitive, it may also be prone to give incorrect results if conducted in a sloppy way without paying due care to all the important details of the procedure.

The theory and practice of Rockwell Testing is most authoritatively exposed in:
ASTM E 18 - Standard Test Method for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials.

An International Standard, issued by ISO - International Standards Organization is also available:
ISO 6508-1 Metallic Materials - Rockwell Hardness Test. Part 1 - Test Method

Note: for information on where to find, see at the end of this Publication.

The importance of learning and understanding Standards requirements cannot be overemphasized.

The most striking feature of this method is that it is spread through 30 different scales, making it one of the most versatile methods, as for any conceivable material and condition there is certainly one combination of force and indenter applicable to the case.

But even limiting ourselves to the three most used scales, called A, B and C, it can be affirmed that these are used for most applications.

The indenter is either a "spheroconical" diamond (called "Brale") shaped in conical form, with an included angle of 120 degrees and with a smoothly rounded tip of 0.2 mm radius), or a hardened ball of one of a range of different diameters (1/16", 1/8", 1/4", 1/2").

The type of Rockwell hardness (the Scale) defined by a letter establishes the indenter and the loads applied, except that for Superficial Rockwell one of three loads has to be also specified.

Performing a Rockwell test consists in:

- putting gently the specimen in contact with the indenter,
- applying a preliminary (or minor) force (load) (of 10 kg for normal or 3 kg for superficial testing),
- automatically or manually zeroing the penetration measuring instrument or dial gage,
- applying gradually the total (or major) force (load) (of 60, 100 or 150 kg for normal and 15, 30 or 45 kg for superficial testing),
- removing gently the total force (load) while leaving in place the preliminary one (so that the elastic deformation following the removal of final force (load) is recovered),
- measuring the depth of penetration using the instrument,

- and finally calculating the Rockwell hardness number as the difference between a fixed value (100 for Brale 130 for ball) and showing it on a dial or on a digital display.

The Rockwell hardness number is therefore an expression of the depth penetrated by the indenter between the application of the preliminary force (load) (when the instrument is zeroed) and the removal of the total force (load), with the preliminary force (load) still in place (see the expressions at the end of this section).

Because of the nature of Rockwell testing, which essentially measures the vertical movement of the indenter, any disturbance introducing an error in this measurement produces a false reading.

Any error of only 0.002 mm in the measurement of the vertical displacement produces an error of one Rockwell point, in regular test. For superficial test the error needs only be 0.001 mm for one hardness point.

Therefore any minor chip or burr on the underside of the specimen must be eliminated before testing. It is good practice to discard the first test whenever changing anvil or indenter, to make sure that any minor disturbance is crushed.

Also the anvil must seat squarely in place with no excess oil, grease or dirt under its support area. Finally the test piece must be fully supported, no overhanging is admitted: if necessary an auxiliary support (not a hand) must keep the test piece in place, so that no movement will occur when applying the final load. This applies also for curved surfaces.

If the indenter comes in contact with the anvil, if it falls or is subject to an occasional impact, it must not be used before verifying under a microscope that the tip is not cracked or blunt.

The emplacement of the Rockwell tester must be free from vibrations. No indentation can be performed twice on the same spot. The minimum thickness of part or test piece is to be observed, (at least 10 times the depth of the indentation expected) according to the Standard, and the minimum distance to the edge or between impressions should again be at least 2.5 or 3 times their size.

The readings are exact for flat specimens. If curved or round specimens are to be tested there is a correction (dependent on the diameter and on the hardness range) to be applied as detailed on Tables of the Standard, at least up a diameter of one inch (25.4 mm).

Hardness values are to be reported by writing the number followed by the letters HR for Hardness Rockwell and affixing the name of the scale used: i.e. 32 HRC.

The same caution as explained above should be used when attempting to find correlations among different scales, as they must be considered as only approximations.

The formulas used for calculating Rockwell Hardness values are as follows:

For regular Rockwell Hardness using spheroconical "Brale" Indenter:

HR[Scale] = 100 - h/0.002
where Scale is A, C, D and h is the depth penetrated in mm.

For regular Rockwell Hardness using a steel ball

HR[Scale] = 130 - h/0.002
where Scale is B, E, F, G etc. and h is in mm

For Superficial Rockwell Hardness using either indenter

HR[(total load) Scale] = 100 - h/0.001
Where total load is 15, 30 or 45 kg
and Scale is N (for "Brale") or T (for 1/16" ball)
and h is in mm.

6. INFORMATIONS

ASTM Standards are obtainable at:
American Society for Testing and Materials
100 Barr Harbor Drive
West Conshohocken
PA 19428-2959
USA
Phone (610) 832 9500
FAX (610) 832 9555
e-mail: service@astm.org
website: http://www.astm.org

International Standards can be obtained through
ANSI - American National Standards Institute
http://www.ansi.org/

ISO - International Organization for Standardization
http://www.iso.ch/

Also available as free download or hardcopy:
NIST Recommended Practice Guide
Special Publication 960-5
Rockwell Hardness Measurements of Metallic Materials
by Samuel R. Low
http://www.nist.gov/practiceguides

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