COURSE NAME: MME – 102

GROUP NO.: A1

EXPERIMENT NO.: 03(b)

NAME OF THE EXPERIMENT:

Mechanical testing of materials – Hardness (RH, BH, VH/ Microhardness, Shore hardness) test of metals, ceramics, and polymers

DATE OF PERFORMANCE:

20. 10. 2024

DATE OF SUBMISSION:

26. 10. 2024

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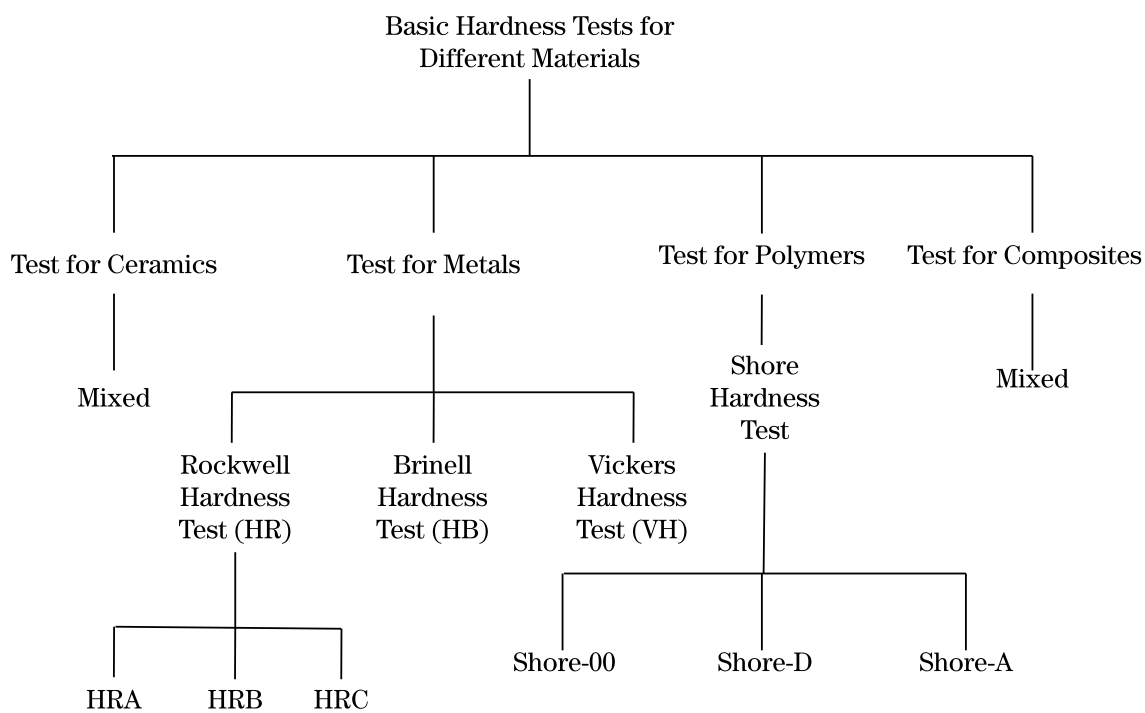
Introduction

Hardness is a measure of materials resistance to localised plastic or permanent deformation, such as indentation or scratching. A material with higher hardness indicates that it is more resistant to scratch or indentation than the materials with lesser hardness. This hardness is influenced by various factors like materials composition, microstructure, grain size, strain hardening, testing conditions etc. This characteristic of material relates to its mechanical properties. Sometimes even different properties are understood through the measurement of hardness. For example, yield strength and ultimate tensile strength (UTS) usually increases with the increase of hardness, thus it often requires a hardness test rather than a tensile test. This important mechanical property has been measured through ages. The measurement or scaling through Mohs Scale is an old technique where materials are scaled from a rating of 10 to 1 indicating a gradual decrease of hardness in a qualitative scale. Now with more advanced and precise equipment, we can measure the quantitative values of the hardness of a material. There exists different equipment for different materials hardness measurement. Thus, various hardness measurement processes for different materials have been introduced, for example, Rockwell, Brinell, Vickers, Knoop or Shore hardness tests for metals, ceramics, polymers and composites. Here is a diagram introducing basic hardness tests:



In this experiment, we particularly focused on measuring hardness using Rockwell, Vickers and Shore hardness tests.

Equipments

- Rockwell Hardness Tester
- Vickers (Microhardness) Hardness Tester
- Shore 00 Hardness Tester
- Different materials for hardness test

Procedure

Rockwell Hardness Test

1. HRB
    a. For the HRB test, we took three samples. Among non-ferrous samples, we took pure Aluminium and casted Aluminium. Among ferrous samples, we took cast iron for the HRB test.
    b. Sample preparation: We prepared our specimen in such a way that it has a flat and smooth surface.
    c. Then we calibrated the Rockwell Hardness Tester to 100kg load.
    d. Select the dwell time for 15 seconds.
    e. Placed our specimens one by one in the tester plane.
    f. We took 1 reading per specimen.

2. HRC
    a. For the HRC test, we again took three samples, which are medium carbon steel, alloy steel and cast iron.
    b. Sample preparation: We prepared our specimen in such a way that it has a flat and smooth surface.
    c. We calibrated the Rockwell Hardness tester to 150 kg load.
    d. Placed our specimens one by one in the tester plane.
    e. Then took 1 reading per specimen.

Vickers Hardness Test

1. Prepared our sample with a polished and plane surface, so that microhardness can be measured with less error and the microscope could easily observe the indentation size.
2. Two different materials– a. Metal sheet (one side paint coated) b. A railway clip – were taken for the hardness test.
3. For the metal sheet, calibrate the microhardness tester to the test load to 1Kgf.
4. For the railway clip, calibrate the microhardness tester to the test load to 3Kgf.
5. Select the dwell time for 10 seconds.
6. Calibrate the anvil with the rotating wheel to such a position from where the microscope can observe the sample bright.
7. We took 3 readings for the metal sheet and 2 readings for the railway clip.

Shore Hardness Test

1. We took the shore-00 hardness tester and placed it— i. Once in a teflon plane, ii. Once in a glass plane.
2. Took the reading for both of the cases.

Results

Table-1: Results from the Rockwell Hardness test

Scale	Material		Dwell Time (sec)	Test Load (Kgf)	Hardness
HRB	Non-ferrous	Pure Al	15	100	-57
		Casted Al			48.3
	Ferrous	Cast Iron			84.3
HRC	Non-ferrous	Alloy Steel	15	150	59.6
		Medium Carbon Steel			28.5
	Ferrous	Cast Iron			-2.0

As HRB and HRC does not directly have a correlating equation for scale conversion, we used HRB and HRC to Brinell Hardness conversion chart and applied it to get our Rockwell hardness values to the Brinell Scale.

Table-2: HRB and HRC to Brinell Hardness scale conversion

Rockwell Hardness Type	Sample	Value	Brinell Scale (500kg)	Brinell Scale (3000Kg)
HRB	Pure Al	-57.9	N/A	N/A
	Casted Al	48.3	82	N/A
	Cast Iron	84.3	140	N/A
HRC	Alloy Steel	59.6	N/A	647
	Medium Carbon Steel	28.5	N/A	277
	Cast Iron	-2.0	N/A	N/A

Table- 3: Result from the microhardness (Vickers) test

Material	Readin g	Test Load (Kgf)	Dwell time (sec)	d_1 (µm)	d_2 (µm)	VHN	VHN avg	Identified Metal
Metal Sheet	01	1	10	148.8	157.6	82.2	74.8	Low carbon steel
	02			171.3	159.3	67.9		
	03			163.5	152.5	74.3		
Railway Clip	01	3	10	161.7	168.3	204.3	200.7	High carbon steel
	02			166.9	169.1	197.1		

Table- 4: Result from Shore-00 hardnesstest

Hardness Tester	Material	Shore Hardness
Shore-00	Teflon foam	16 Kgf
	Glass	68 Kgf

We calculate the Vickers hardness number (VHN) with the equation:

$$VHN = \frac{1.8544P}{d^2}$$

Using this equation, we calculate VHN for all d_1 and d_2 and compare it with our machine values in the next table.

Calculation:

Average value of diameter, d = (d1 + d2)/2

For Metal sheet: Reading 1: d = (148.8 + 157.6)/2 = 153.2 µm
2: d = (171.3 + 169.3)/2 = 165.3 µm
3: d = (163.5 + 152.5)/2 = 158 µm

For Railway Clip: Reading 1: d = (161.7 + 168.3)/2 = 165 µm
2. d = (166.9 + 169.1)/2 = 168 µm

VHN for, Metal sheet:Reading 1: VHN = $(1.8544 * 1)/(153.2 * 10^{-3})^2 = 79.01$ Kg/mm^2
2: VHN = $(1.8544 * 1)/(165.3 * 10^{-3})^2 = 67.86$ Kg/mm^2
3: VHN = $(1.8544 * 1)/(153.2 * 10^{-3})^2 = 74.28$ Kg/mm^2

Average VHN = (79.01+67.86+74.28)/3 = 73.74 Kg/mm^2

Railway Clip: Reading 1: VHN = (1.8544* 1)/(165* 10^{-3})^2= 200.7 Kg/mm^2
2: VHN = (1.8544* 1)/(168* 10^{-3})^2= 197.108 Kg/mm^2

Average VHN = (200.7+197.108)/2 = 200.7 Kg/mm^2

Table-5: Comparison and error calculation of the Vickers Hardness test

Material	**Reading**	**d = $(d_1+d_2)/2$ (μm)**	**VHN (calculated) (Kg/mm^2)**	**VHN avg (calculated) (Kg/mm^2)**	**VHN avg (Kg/mm^2)**	**Error**
Metal Sheet	01	153.2	79.01	73.74	74.8	1.43%
	02	165.3	67.86			
	03	158	74.28			
Railway Clip	01	165	204.34	200.7	200.7	0%
	02	168	197.108			

Discussion

** Explain the working procedure of Brinell, Vickers and Rockwell Hardness tests, write about their scales, indenters and indentation geometry, load application, how hardness is measured. Use appropriate sketches and compare the 3 methods. Also talk about the specimen thickness limitations for all hardness tests.*

On the Rockwell Hardness Test:

In the Rockwell hardness test, we did two different kinds of testing, one in the B scale (HRB) and the other in the C scale (HRC). The tester we had in the laboratory had various scales, for example: HRA, HRB, HRC, HRD, HRE, HRH and HRS. But for specific reasons, we had to use only HRB and HRC. And for other scales or specimen tests, rather using D, E or etc scales, we moved on to the Vickers hardness test. We were given two different types of specimen, one ferrous (Cast iron) and another non-ferrous (pure Al, casted Al, alloy steel and medium carbon steel).

The non-ferrous metals used were prepared before going through the test. For example, the cast iron sample we used went through heat treatment and polishing. Otherwise, the sample could not hold the amount of force given on its surface because HRB and HRC– both are hardness tests for hard metals.
Looking into the table of the data collected from the Rockwell hardness test, we see that the pure aluminium gives a negative HRB value. This indicates that pure Al is too soft for the HRB scale to be put into.

Rockwell hardness test B and C have different types of hardness measurement techniques. HRB uses a steel ball (diameter 1/16 inch) as its indenter. On the other hand, HRC uses a diamond brale as the indenter. But as for all the other Rockwell hardness tests, both HRB and HRC use 'depth of indentation' for hardness measurement. Firstly, we put a minor load on our specimen, then we put a major load on it, for which the indenter penetrates the sample more (t and we get a depth difference t mm as shown in the figure.

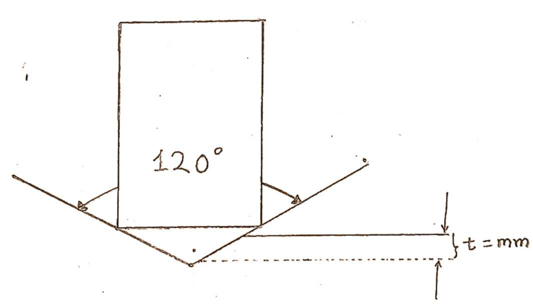


Fig: A hand-drawn sketch showing use of the depth of indentation in the Rockwell Hardness test.

Sample pictures from the Rockwell Hardness Test:

HRB: Pure Al

HRB: Cast Iron

HRC: Medium Carbon Steel

HRB: Casted Al

On the Brinell Hardness Test

Brinell hardness tests have a steel ball (diameter, D= 10 mm) penetrating into the material and then the diameter of the circular penetration is used to measure the hardness of the material. The penetration creates a circular trench. We take two side diameters d1 and d2 and average it into $d = (d_1 + d_2)/2$ (for more precise values). Then use this in the equation of calculating Brinell Hardness Number (BHN):

$$BHN = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})}$$

The unit for BHN is Kgf/mm^2. On the other hand, Rockwell hardness test values are indicated with the test name (RHA, RHB etc.).

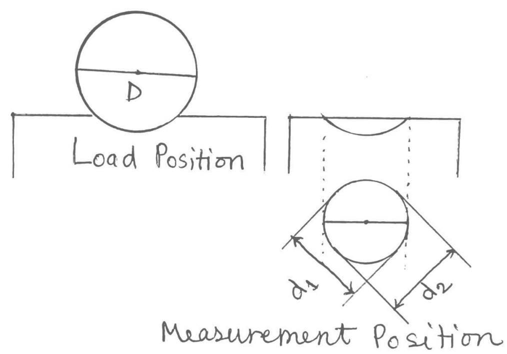


Fig: A hand-drawn sketch showing use of the diameter of penetration in the Brinell Hardness test.

On the Vickers Hardness Test:

The Vickers hardness test is a part of the microhardness test. The indenter of a Vickers hardness test is a diamond with a base pyramid. The indentation made on a sample is very small, thus it takes a microscope to see the indentation. The load range was 1Kg– 50 Kg and 800– 850 VHN (Vickers Hardness Number) could be calculated with our microhardness machine.

In the Vickers hardness test, we use a diamond pyramid with a square base and is viewed under a microscope. The square base pyramid indenter has a diamond on its apex. If seen from the side view, the angle of the pyramidal tip would be seen as 136 degrees. On the surface of the specimen, it creates a diamond shape (or a square) and we measure both of its diagonal length for precisement. Shown in the next figure.

In our first test with the metal sheet (paint coated on one side), we took three readings and the values ranged from lowest VHN 67.9 to 82.2. In the second specimen, we took a railway clip. In this test, we saw two of the readings as VHN 204.3 and 197.1. We calculate the Vickers hardness number (VHN) with the equation:

$$VHN = \frac{1.8544P}{d^2}$$

Here P is the value of test load in Kgf and d is the average value of the diameter of the indenter which means, d = (d1 + d2) /2.

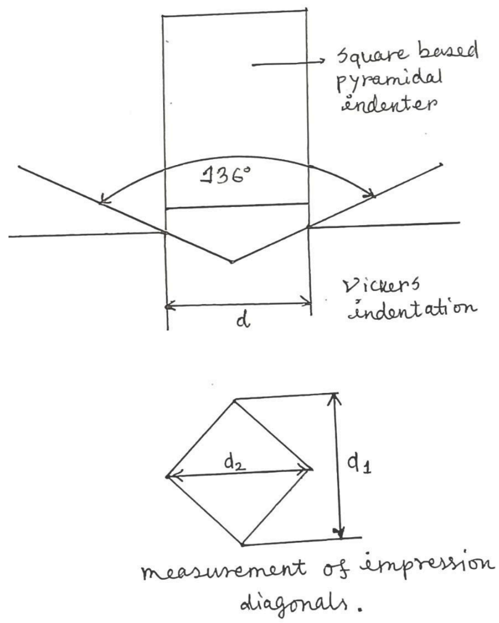


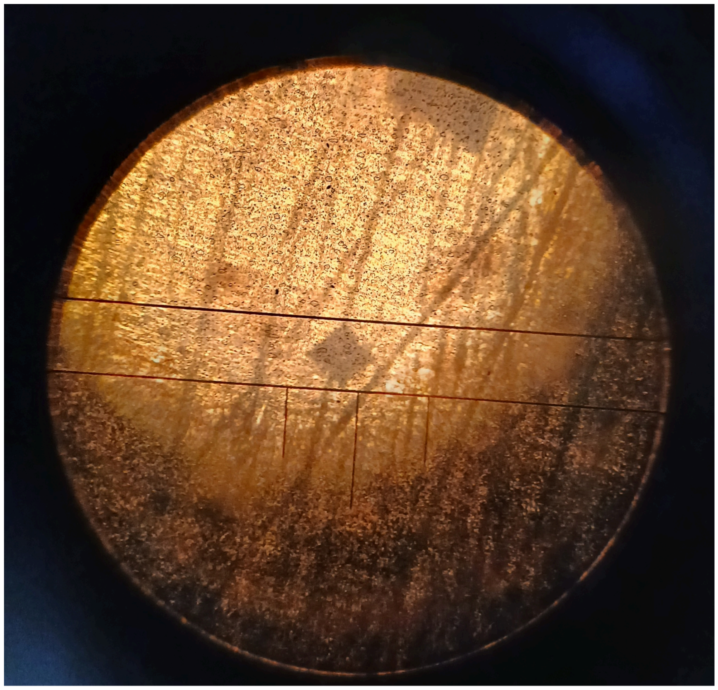
Figure: Vickers indentation and measurement of impression diagonal

From the table, after comparing VHN values, we can easily say that, as the railway clip has more VHN value than the metal sheet, the railway clip contains more carbon (metal alloy) than the metal sheet.

Sample Pictures from the Vickers Hardness Test

Vickers; On Rail-Clip

Vickers; Metal sheet



Microscopic observation of the diamond shaped Vickers indentation

Comparison between the three methods:

Rockwell Hardness Test	**Vickers Hardness Test**	**Brinell Hardness Test**
Diamond Cone Indenter	Diamond Pyramid Indenter	Hardened Steel Ball Indenter
Measures depending on the depth of penetration	Measures depending on the diagonal length of the indentation	Measures depending on the diameter of the indentation
Fast Process (15 sec dwell time)	Fast Process (10sec dwell time)	Slow Process
Takes minimal effort in sample preparation	Takes high effort in sample preparation	Takes minimal effort in sample preparation
Used for metals, alloys, plastics etc	Used for metals, ceramics and hard materials etc.	Used for ferrous and non-ferrous metals
Macro-hardness test	Microhardness test	Macrohardness test

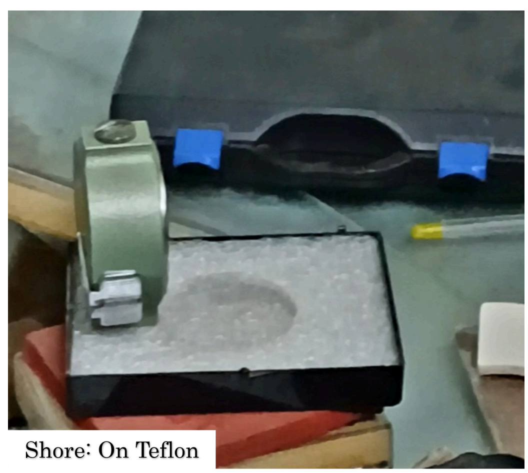
On the Shore Hardness Test:

Shore hardness test is the basic hardness testing process for almost all types of polymers. In the experiment, we were demonstrated 3 different types of shore hardness measuring machines: shore-A, shore-D and shore-00 . Shore-A is used for hard polymers such as: polypropylene. Shore-A is used for less hard or medium hardness polymers, the type of polymer that are used in sponge sandals, leather seats, tubes and tires of the wheels of vehicles. Finally, the shore-00 hardness tester is used for low hardness polymers. We used shore-00 to measure the hardness of a small teflon sheet and a tempered glass (upper layer of a table). We took one reading per material and made the table with our test values.

For a hardness test to produce accurate and trustworthy findings, the specimen's thickness is essential. The indenter may pierce the material if the specimen is too thin, which could harm the underlying surface and alter the test results. At least 10 times the anticipated indentation depth should be present in the specimen thickness. By doing this, the indenter is prevented from reaching the bottom surface and affecting the test results. For instance, the minimum specimen thickness should be 1 mm if the anticipated indentation depth is 0.1 mm.

Sample pictures from the Shore hardness Test


Shore: On Glass


Shore: On Teflon

** What are the limitations for distance from specimen edge to indentation and distance between indentations? Explain the consequences of not adhering to these limitations.*

The distance from the edge of a material and the indentation sight is necessary to protect the material from edge defects. If the indentation is done on the edge, it might occur a permanent destruction due to the test load given by the indenter. That is why at least 2.5 times the indentation's diameter must separate the specimen's edge from the indentation's centre.

In the case of ensuring distances between the indentations, at least three times the indentation's diameter should separate the centres of two consecutive indentations. This spacing guarantees that the stress concentration at the specimen's edge won't affect the indentation, which could produce unreliable findings.

** What surface condition is necessary for Brinell, Rockwell and Vickers? Why is a smooth polished surface more important for one specific hardness test and what are the consequences of having a rough uneven surface?*

In all three tests of Brinell, Rockwell and Vickers test, the surface conditions must come to a certain standard. Preconditions are— a. The surface must be polished well (specially in Vickers), b. The surface must stay flat with the anvil, c. The two surfaces of a specimen should be parallel, otherwise it may tilt and might result in an errorful measurement.

Surface smoothness of a specimen is specially necessary in the case of microhardness test. Because firstly, this test is conducted in a very small (micro) location of a comparably larger sample. If the sample is not smoothly polished enough, the indenter would not detect the specific indentation region easily and would result in an uneven indentation. Secondly, in the Vickers (microhardness) test, the specimen and the indentation is observed through a microscope. Even a not-so-well polished or rough surface can lead us to uneven and unparalleled reflection of the light emitted from the microscope. As a result, we would not be able to see the microscopic picture clearly without a fine surface polish.

** Discuss why d1 and d2 values for Vickers hardness test varied? Also discuss the variation in Calculated VH values and the ones obtained directly from the machine.*

In the Vickers Hardness Test, we took 5 readings on 2 different specimens. In the first specimen of the metal sheet, we see in all three readings that d1 and d2 are different with unusual error.

The reason for this seemingly high error was the surface of the metal sheet. While conducting the experiment, we observed that the surface of the sample was not polished enough. We can surely assume that it was the reason for the error.

In the second specimen (railway clip), we again see that the readings of d1 and d2 in this case also have an error. We presumed that the reason for this error was the clip not being flat. It was tilted with the anvil. We used a slice of metal banking to make the clip tilt less. Though, that led us to different values of d_1 and d_2 and thus VHN.

** In Shore hardness tests, explain why measuring bulk property is difficult and only surface property is measured?*

In shore hardness tests, we use such test equipment which indents the specimen on the surface of a polymeric material. In the test, as the indentation is only happening on the surface, there is no exact assurance that the bulk hardness of the polymeric material would be the same. Because, in most of the polymeric material, as we go deep down from the surface, its density changes. But we cannot measure it in that deep because that would take the material to fully destruct. It might also happen that the entire material is made of different polymers while the surface is made with one single polymer. As a result, while measuring the shore hardness, we only get to know the certain hardness value only of the surface, not the bulk material.

** Discuss the variation in hardness values for all samples tested in Rockwell and Vickers and Shore test.*

Hardness Test	**Specimen**	**Experimental Value**	**Official Value**
HRA	Pure Al	-57.9	N/A
	Casted Al	48.3	20-50
	Cast Iron	84.3	N/A
HRB	Alloy Steel	59.6	15-58
	Medium Carbon Steel	28.5	10-70
Vickers	Metal Sheet	74.8	22-661
	Railway Clip	200.7	182-748
Shore	Teflon foam	16 Kgf	N/A
	Glass	68 Kgf	N/A

Usually, all the non-applicable terms mentioned in the official values are measured in some other hardness scale. For the values stated in the official part, those are in or close to the official hardness range on that specific hardness measuring scale.