Lab 1: Mechanical Testing – Hardness Testing

Objectives

The objective of the Lab is to characterize the **material hardness** and relate it to other materials properties, including:

1. Understand the fundamentals of hardness, its definition, and calculation methods.
2. Learn hardness measurement techniques using standard testing machines including Brinell and Rockwell hardness testers.
3. Its relation to other mechanical properties such as tensile strength; estimate their expected values.
4. Execute statistical analysis of experimental data.

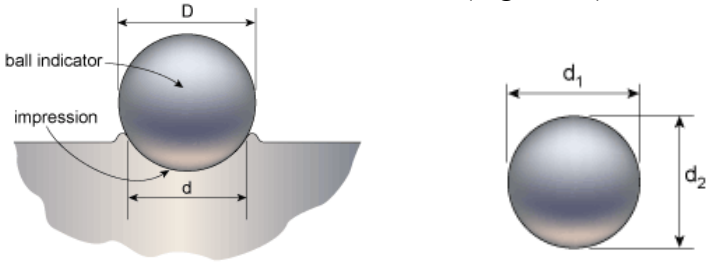
Background

Hardness

Hardness is a measure of a material's resistance to surface penetration by an indenter having a force applied to it. During hardness testing, indenters made from hard materials (hardened steels or diamond) is pressed into the surface of the test piece causing a formation of permanent indentation (imprint) in its surface. There are many hardness testing procedures, each using a specific set of testing parameters including indenter geometry and material, load, and corresponding formula to calculate hardness. In general, hardness, **H**, is determined from the relationship between load and deformation (e.g. penetration depth, impression area). Hardness tests are usually considered as non-destructive tests and are frequently substituted for tensile tests in specifications and in quality control.

Brinell Hardness Test

Brinell hardness testing is a commonly used hardness testing technique (Figure 1). Typically, this test uses a 10 mm diameter ball made from hardened steel (Figure 1a) and standard loads of 500, 1000, 1500, 2500 or 3000 kilograms. To determine the hardness, the diameter of the impression needs to be measured after the indentation (Figure 1b).



(a) (b)

Figure 1. Schematics showing (a) the side view during a Brinell hardness testing, and (b) the top view of the surface impression after the indenter is unloaded.

Brinell hardness number (BHN) is calculated as the load, ***P***, over the indentation impression area (the stress on the indented surface) using the following equation:

$$BHN = \frac{P}{\frac{\pi D}{2}\left(D-\sqrt{D^2-d^2}\right)} \quad (1)$$

Where, ***P*** is the applied load in kilogram, *D* is the diameter of the indenter ball (10 mm), and *d* is average measured impression rim diameter in millimeters.

Estimate **Ultimate Tensile Strength** using hardness data

As previously discussed, hardness is related to the strength of material. The ultimate tensile strength, UTS, of metals and alloys (e.g. steels) can be roughly estimated from the Brinell hardness number:

UTS (psi) = 500 x HBN
or
UTS (MPa) = 3.45 x HBN (2)

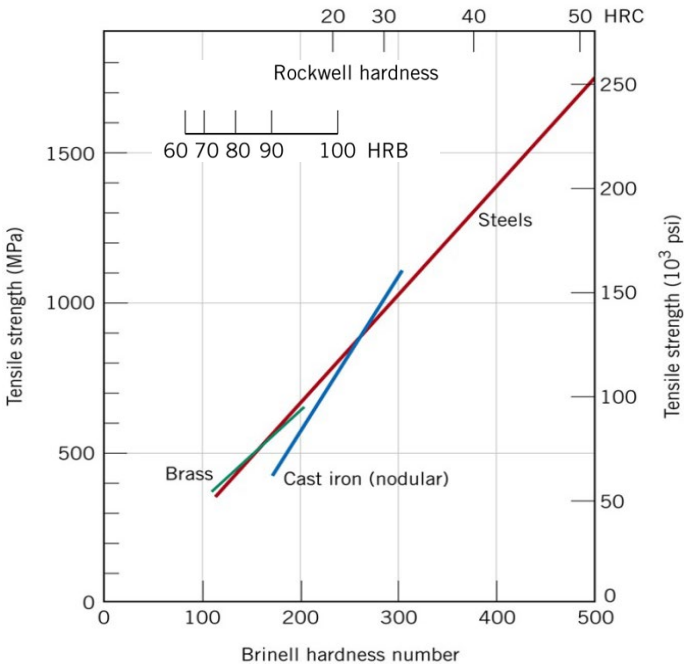


Figure 2. Relationships between hardness and tensile strength for steel, brass, and cast iron.

Rockwell Hardness Test (*details in the ASTM E18-15*)

Rockwell hardness testing uses a combination of various indenters and loads. In the Rockwell hardness test, a minor load of 10 kgf is first applied. This causes an initial penetration of the indenter and then a major load is applied causing additional penetration. The penetration depth caused by the major load is automatically measured by the Rockwell machine and converted to a scale value displayed by the machine. The number obtained is Rockwell Hardness Number. The Rockwell Hardness Number (on various scales such as A, B, C, D, E, F, G, H, K, and N specified by the depth of indenter and the applied load) is a number inversely proportional to the depth of indentation (t) into the specimen under a specified load.

Table1. Common Types of Rockwell Hardness Test

Test	Load (kgf)	Indenter	Formula to calculate hardness number
A	60	120° diamond cone	HRA = 100 - 500 *t*
B	100	1⁄16-inch-diameter steel sphere	HRB = 130 - 500 *t*
C	150	120° diamond cone	HRC = 100 - 500 *t*
D	100	120° diamond cone	HRD = 100 - 500 *t*
E	100	1⁄8-inch-diameter steel sphere	HRE = 130 - 500 *t*
F	60	1⁄16-inch-diameter steel sphere	HRF = 130 - 500 *t*
G	150	1⁄16-inch-diameter steel sphere	HRG = 130 - 500 *t*

t - indenter's depth of penetration.

Scale-B of the Rockwell Test:

The Rockwell-B test uses a 1/16-inch steel ball indenter with a major load of 100 kgf and is primarily used for copper alloys, soft steels, aluminum alloys, malleable irons, etc. HRB is used to denote the hardness obtained from this test.

Scale-C of the Rockwell Test:

The Rockwell-C test uses a spheroconical diamond Brale indenter with a major load of 150 kg and is primarily used for steel, hard cast irons, case hardened steel and other materials harder than 100 HRB. HRC is used to denote the hardness obtained from this test.

Conversion between different hardness scales (*see ASTM E140-12b*)
Hardness may be converted between different scales using conversion tables, which are available from many sources. Table 2 shows an example of the hardness conversion table.

Table 2. Hardness conversion table.

HV Vickers	HB brinell	Rockwell		UTS (N/mm²)	HV Vickers	HB brinell	Rockwell		UTS (N/mm²)
		HRC	HRB				HRC	HRB	
450	428	45.3		1455	225	214	-		720
440	418	44.5		1420	220	209	-	97	705
430	410	43.6		1385	215	204	-		690
420	400	42.7		1350	210	199	-	95.5	675
410	390	41.8		1320	205	195	-		660
400	380	40.1		1290	200	190	-	94	640
390	371	39.8		1255	195	185	-		625
380	361	28.8		1220	190	181	-	92	610
370	352	27.7		1190	185	176	-		595
360	342	36.6		1155	180	171	-	90	575
350	333	35.5		1125	175	166	-		560
340	323	34.4		1095	170	162	-	87	545
330	314	33.3		1060	165	156	-		530
320	304	32.2		1030	160	152	-	84	510
310	295	31		995	155	147	-		495
300	285	29.8	106.5	965	150	143	-	81	480
295	280	29.2		950	145	136	-		465
290	276	28.5	105.5	930	140	133	-	77	450
285	271	27.8		915	135	128	-		430
280	266	27.1	104.5	900	130	124	-	73	415
275	261	26.4		880	125	119	-		400
270	257	25.6	104.5	865	120	114	-	68	385
265	252	24.8		850	115	109	-		370
260	247	24	103.5	835	110	105	-	63	350
255	242	23.1		820	105	100	-		335
250	236	22.2	102	800	100	95	-	57	320
245	233	21.3		785	95	90	-		305
240	228	20.3	100	770	90	85	-		285
235	223	-		755	85	80	-		270
230	219	-	98.5	740	80	76	-		255

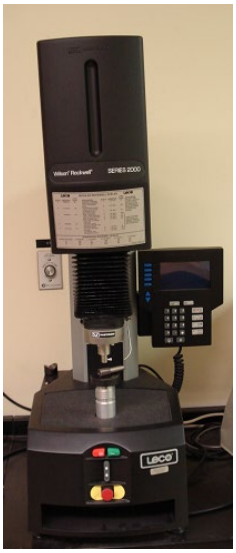
Lab Procedure

Safety: all personnel are required to wear safety glasses at all time in this lab.

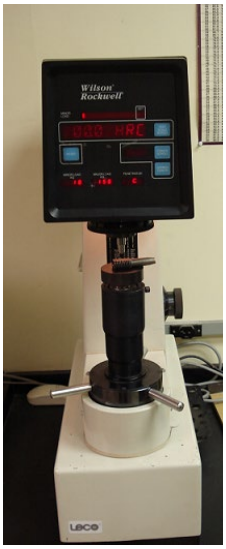
A. Apparatus

Commercial machines will be used to perform Brinell and Rockwell hardness tests (Figure 2).

Wilson BH 300 Brinell Hardness Tester



Wilson Rockwell Series 2000 Hardness Testing Machine



Wilson Rockwell Series 500 Hardness Testing Machine

Figure 3. Hardness testers used in this lab.

The Rockwell test is the most common and easiest hardness test to perform. The Rockwell machine has a variety of indenters and uses several different applied loads which can be selected to fit the general hardness of the metal or alloy being tested. Hardened steel, for example, would need the conical diamond indenter with the 150 kg load ("C" scale). Steel that has not been hardened and many nonferrous alloys would require a 1/16 inch ball indenter with the 100 kg load ("B" scale). The hardness number is read directly from the dial on the machine. There are two scales on this dial so it is important to read the one appropriate for the range being used.

The Brinell Hardness Tester, like the Rockwell, forces an indenter into the surface of the material. It uses a larger ball, 10 mm diameter, which is loaded from 500 to 3000 kg. The diameter of the impression is measured with a microscope (Figure 4) and this reading is used to obtain the Brinell Hardness Number from a chart. The Brinell test is used on larger parts or samples and is more frequently used on castings or material of coarse microstructure.

Figure 4. Viewing scope.

B. Specimens

You will test samples provided in your set box. Each student will test at least two samples: (1) the steel samples prepared for the impact, Charpy, test, and (2) a non-ferrous sample, such as aluminum alloys, brass, copper, or polymers prepared for tensile and/or 3-point bending tests. Selection of the proper machine for each specimen will be done by the student groups based on

the specimen type, size, shape and condition. **At least five indentation tests** should be performed on each specimen to obtain meaningful statistics.

C. Hardness Tests

The procedure to operate each machine will be discussed in details below as well as demonstrated by the instructor or TA.

Brinell Hardness

1. Turn on the main switch located near the top right side of the machine.
2. Setup the correct indenter - 10mm ball. When set, screw the end cap back on the impinging cylinder head.
3. Select load.
4. Place the sample material specimen in the center of the test platform. You are now ready for testing.
5. Testing: Lower the cylinder head until it touches the sample.
6. Once the correct load is reached, retract the impinging cylinder head so the sample may be removed for analysis.
7. Analysis: Place sample under the Brinell Hardness Specimen Viewing Scope.
8. Measure and record the indent formed during testing on the sample with the scale in the viewing scope's eyepiece (Figure 5)

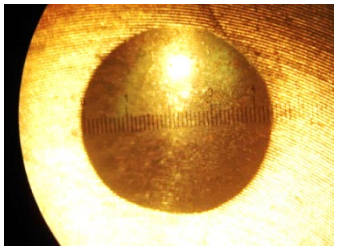


Figure 5.

Rockwell Hardness

1. Turn on the **Wilson - Rockwell Series 2000** Hardness Testing Machine and wait for the self-test on the screen to be over and press ok (Fig. 6).
2. Move the impinging cylinder head to the up position with the actuation buttons (Fig. 7).
3. Select the desired test scale from the screen (Fig. 8) and install the appropriate indenter for the test being performed (Fig. 9).

Figure 6

Figure 7

Figure 8

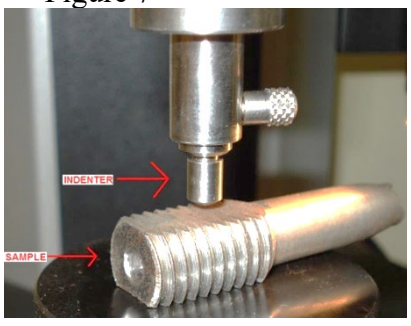


Figure 9

4. Bring the indenter head close to the sample using the actuation buttons (Fig. 9).
5. Press start and wait a few seconds for the test to complete. Read and record the necessary data (Fig. 10). Make sure you move the sample slightly between tests as not to indent the same area.

Figure 10.

6. Repeat the previous step a desired number of times for an average value. Press the "Statistics" button for readout of all the data.

***Use of* Wilson - Rockwell Series 500 (optional)**

1. Turn on the Wilson - Rockwell Series 500 Hardness Testing Machine.
2. Move the test platform down using the spinning handles (Fig. 11).
3. Select the desired test scale using the "Test Scale Scroll" button (Fig. 12) and install the appropriate indenter for the test being performed (Fig. 13).
4. If the "MAJOR LOAD KG" screen is flashing, select the appropriate Major Load to match the number given on the screen using the Major Load Selector Knob on the side of the testing machine (Figure 14).

Figure 11.

Figure 12.

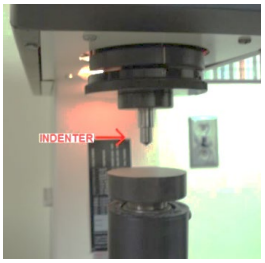


Figure 13.

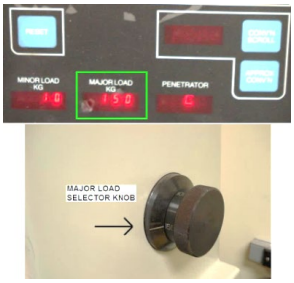


Figure 14

5. Place sample on the test platform.
6. Move the test platform up gently using the spinning handles until the "Minor Load" screen reaches the "Set" position (Figure 15), and the test will start automatically.
7. Record the readout of the sample's hardness from the screen (Figure 16).
8. Repeat the previous step a desired number of times for an average value. Make sure you move the sample slightly between tests as not to indent the same area.

Figure 15

Figure 16.

Requirements for Lab Report (individual report)

Content of "**Objectives**" and "**Methods and Materials**" is described in the file "Guidelines-Requirements_...".

Materials: Present materials that you analyze in the table format with composition, specification, expected Hardness and UTS.
Steel alloys: 1018, 1045, 4140, 1095 (CF, HR, W1)
Aluminum alloys: 2024-T351, 3003-H14, 6061-T651, 7075-T651
Copper (Multipurpose 110 Copper)
Common Brass: (Cu 63wt% and Zn 37wt%)
Bronze (Weldable 954)

"**Experimental Results and Data Analysis**" must include (detailed procedure presented in the Appendix below):

- The raw data for at least 3 different materials (Rockwell measurements) and 2 materials (Brinell measurements) must be analyzed. For each chosen material you must process at least 15 individual measurements.
- Statistical analysis of your data including mean value, standard deviation, and confidence interval.
- Calculations or other actions required to determine:
  - Brinell Hardness Number based on the diameter measurements and Eq.1.
  - Rockwell Hardness Numbers (HRA, HRB, HRC or any other relevant scales).
  - Conversion from Rockwell to Brinell Hardness.
  - Conversion to ultimate tensile strength (UTS).

"**Discussion**" must include answers to the following questions:

1. Correlation between obtained parameters and specimen composition and other specifics.
2. Compare the Rockwell hardness for different alloys and explain the reasons for their differences.
3. Comparison between your experimental data and the literature values.
4. Possible sources of uncertainty (lack of repeatability). *See ASTM_E18-15, ch.X2.5.*
5. Write down how you estimated UTS from the hardness data.
6. Why is the Brinell test used on material with coarse microstructure?

In **"Conclusion"** you shortly repeat the conclusions that you formulated in the "Discussion" and summarize the results and analyses that supported them. Other comments regarding the overall Lab is also welcome here.

APPENDIX
Experimental Data and Data Analysis

All raw data and data analysis must be presented in the form of tables.

Rockwell Tests

1. Review all raw data and choose data sets for 3 different materials that you will analyze.
2. Three different materials could be either materials from the same group, for an example 3 different steel alloys, or 3 aluminum alloys, or they can be from different groups – one steel, one aluminum alloy, and one copper alloy. Then create an Excel spread sheet based on them.
3. For each chosen material you must process at least 15 measurements (3 groups by 5 individual measurements) disregarding "bad" measurements. Definition for "bad" measurements is "the data point is more than 10% from the mean value". Remember that analyzed measurements must consist of, be made on, the same scale.
4. Calculate mean value, standard deviation, and confidence interval for confidence level 95% (https://www.mathsisfun.com/data/confidence-interval-calculator.html). More detailed analysis of measurements results explained in the ASTM E18-15.
5. Convert Rockwell hardness to Brinell hardness number using ASTM E140-12B. Find the most appropriate conversion table and reference it.
6. Convert Brinell hardness number to the ultimate tensile strength (UTS) using corresponding equation from the lab manual. Include confidence interval in this conversion.

Confidence Interval	Z
80%	1.282
85%	1.440
90%	1.645
95%	1.960
99%	2.576
99.5%	2.807
99.9%	3.291

Brinell Tests

1. Choose at least **two different materials** that you will analyze. They can be the same as have been analyzed for Rockwell hardness.

2. Find minimum 3 sets of measurements, then total number of individual measurements must be not less than 15. In this process disregard "bad" measurements using the same approach as was performed for Rockwell data analysis.

3. Calculate mean value, standard deviation, and confidence interval for confidence level 95%.

4. Calculate BHN using the equation from the lab manual. More details are explained in the ASTM E10-18.

5. Convert BHN to the UTS. Include confidence interval in this conversion.

6. Compare the Brinell hardness for the same materials with the results obtained from Rockwell tests.