FACULTY OF ENGINEERING TECHNOLOGY

CAMPUS GROUP T

Lab report Materials Science phase 1

Hardness measurements

3/04/2025

10/04/2025

Darius-Andrei Corlan

Valeriia Fomenko

159 E Team 2

Lab responsible:

Ward Drumont

Academic year 2023-2024

1 Introduction

The objective of this experiment is to determine and compare the hardness of various metal samples using the Brinell, Vickers, and Rockwell methods. The lab focuses on evaluating the influence of material treatment such as quenching and plastic deformation on hardness. Appropriate loads and indenters are applied for each method, and multiple indentations are conducted to ensure accuracy.

Results are analyzed using standardized conversion tables [1] to establish correlations between hardness and tensile strength, as well as to assess the suitability of each testing method for different materials and applications.

2 Background/ Theory

The hardness of metals is measured via standardized tests, in which a small indenter of a defined shape is pressed into the material with a certain force. The hardness is then deduced from the dimensions of the indentation remaining after the test (Vickers and Brinell methods) [2, 3]. In the Rockwell methods, the hardness is read directly from the device on a dial gauge, which actually measures the depth of this indentation.

3 Method & Materials

A hardness apparatus is used for the test, in which one mounts the desired indenter, and one adjusts the desired force. A pre-load of 10 kgf is manually applied to the sample beforehand by turning a wheel, pushing the sample against the indenter with a force of 10 kgf. The rest of the measurement is performed automatically: via a mechanism, the main load is applied, held for a few seconds, and then removed.

5 total samples were tested using multiple types of hardness tests — two C-45 steel blocks, one of them being quenched, a brass strip, and two steel tensile samples, one of them having undergone a tensile test. Before testing, we polished the C-45 steel blocks using progressively smoother sandpaper. Firstly, the two C-45 steel cubes and the brass strip are subjected to the Vickers hardness test. Afterwards, all the samples get subjected to the two Rockwell tests. To determine which rockwell test would be appropriate, the Vickers rating is used. Finally, the brass sample is subjected to the Brinell test.

4 Results

4.1 Measurements

4.1.1 Vickers measurements

All of the samples were subjected to a load of 100 kgf and measured with a digital microscope which was able to digitally measure the dimensions of the indentation. The results of these measurements is displayed in table 1.

Table 1: Measurement results of Vickers hardness test

Material	d_1 (mm)	d_2 (mm)
$\text{Steel}_{\text{hardened}_1}$	0.488	0.498
$\text{Steel}_{\text{hardened}_2}$	0.5	0.515
$\text{Steel}_{\text{hardened}_3}$	0.499	0.5
$\text{Steel}_{\text{unhardened}_1}$	1.09	1.118
$\text{Steel}_{\text{unhardened}_2}$	1.067	1.085
$\text{Steel}_{\text{unhardened}_3}$	1.08	1.09
Brass_1	1.06	1.054
Brass_2	1.061	1.048
Brass_3	1.06	1.058

Afterwards, the necessary calculations are done to determine the Vickers hardness, and the results are placed in table 2.

Table 2: Hardness value results of the Vickers test

Material	d_{avr} (mm)	HV_{avr} $(-)$	ΔHV $(-)$	$HV_{standard\ notation}$ $(-)$
$\text{Steel}_{\text{hardened}}$	0.5	741.33	20	(741.33 ± 20)
$\text{Steel}_{\text{unhardened}}$	1.09	156.12	30	(156.12 ± 30)
Brass	1.06	166.33	30	(166.33 ± 30)

4.1.2 Rockwell measurements

By using the results of the Vickers hardness test, the kind of Rockwell test that needed to be used was determined. For the hardened steel, Rockwell C (HRC) was used, whereas for the brass and the unhardened steel, Rockwell B (HRB) was used.

The results of the respective tests are arranged in table 3.

Table 3: Rockwell hardness results for both of the steel blocks and brass strip

Measurement	$\text{Steel}_{\text{hardened}}$ (HRC)	$\text{Steel}_{\text{unhardened}}$ (HRB)	Brass (HRB)
1	67	80	86
2	62	82	86
3	63	81	87
4	61	83	87
5	83	84	88

After taking the average of these values and calculating the error, the final results are displayed in table 4.

Table 4: Final result of the Rockwell hardness tests

Material	HR_{avr} $(-)$	ΔHR $(-)$	$HR_{standard\ notation}$ $(-)$
$\text{Steel}_{\text{hardened}}$	63.2	2	(63.2 ± 2)
$\text{Steel}_{\text{unhardened}}$	82	1	(82 ± 1)
Brass	86.8	1	(86.8 ± 1)

4.1.3 Rockwell B measurements

For both tensile samples, the Rockwell B hardness test was used. The measurements are displayed in table 5.

Table 5: All measurement results of the tensile samples

Measurement	$\text{Sample}_{\text{original}}$ $(-)$	$\text{Sample}_{\text{drawn}}$ $(-)$
1	65	82
2	61	86
3	69	87
4	58	86
5	61	87

Afterwards, the same steps to calculate the error are done as before, the final results being displayed in table 6.

Table 6: Final results of the tensile sample tests

Material	HR_{avr} $(-)$	ΔHR $(-)$	$HR_{standard\ notation}$ $(-)$
$\text{Sample}_{\text{drawn}}$	85.6	2	(85.6 ± 2)
$\text{Sample}_{\text{original}}$	82	1	(82 ± 1)

4.1.4 Brinell for brass

To perform the Brinell test, first the load force has to be calculated. The force is determined to be 60 kgf. Afterwards, the results of the indentation measurements are noted down in table 7.

Table 7: Indentation results of the Brinell test

Measurement	$d_{indentation}$ (mm)
1	0.728
2	0.709
3	0.719
4	0.728
5	0.72

Finally, the final hardness value can be calculated. The results of this calculation are shown in table 8.

Table 8: Hardness measurement results of the Brinell test

d_{avr} (mm)	HB_{avr} $(-)$	ΔHB $(-)$	$HB_{standard\ notation}$ $(-)$
0.721	150	20	(150 ± 20)

4.2 Calculations

4.2.1 Vickers measurement

Eq. (1) calculates the Vickers hardness number (HV) by dividing the applied load (P) by the square of the average diagonal length (d) of the indentation, scaled by a constant factor (1.85) to account for the geometry of the diamond pyramid indenter [4].

$$HV = 1.85 \cdot \frac{P}{d^2} \tag{1}$$

A calculation for the first test of the vickers indentation is:

$$HV = 1.85 \cdot \frac{100}{0.493^2} = 762.8$$

Because Vickers hardness depends on the square of the diagonal length, a relative error in the diagonal measurement results in twice that relative error in the calculated hardness value [4]:

$$\Delta HV = HV(\sqrt{2} \cdot \frac{\Delta d}{d}) \tag{2}$$

To calculate the error of the diameter, both the spread of the indentation diameters and the error of the digital microscope must be taken into account [4]. The formula used is shown in Eq. (3).

$$\delta d = \sqrt{\left(\frac{\frac{2s_d}{\sqrt{n}}}{d_{indent}}\right)^2 + 0.01^2} \tag{3}$$

By using this equation, the error of the indentation diameter can be calculated:

$$\delta d = \sqrt{\left(\frac{\frac{2 \cdot 0.0085}{\sqrt{3}}}{1}\right)^2 + 0.01^2} = 0.1$$

Therefore, the error of the Vickers hardness test can be calculated:

$$\Delta HV = HV_{avr}(\sqrt{2} \cdot 0.1) = 14.6 \approx 20$$

Afterwards, the error rounded to one significant digit to maintain consistency between different types of measurements [5], concluding to a final result of:

$$HV = (741.3 \pm 20)$$

4.2.2 Rockwell measurements

Since the Rockwell measurement results are displayed directly on the hardness testing machine, only the error on the measurement needs to be determined. This is done using the method for determining standard error using standard deviation [5]. Firstly, the standard deviation needs to be determined. This is done using Microsoft Excel's standard deviation formula. Afterwards the error is determined using Eq. (4).

$$\Delta HRB = \frac{s}{\sqrt{n}} \tag{4}$$

By using this equation with the measurements for the drawn tensile sample, the following calculation ensues:

$$\Delta HRB = \frac{2.94}{\sqrt{5}} = 1.316 \approx 2$$

Contributing to a final result of:

$$HRB = (85.6 \pm 2)$$

4.2.3 Brinell for brass

Eq. (5) determines the Brinell hardness number (HB) by calculating the applied load (P) divided by the curved surface area of the indentation, based on the indenter diameter (D) and the measured indentation diameter (d) [4].

$$HB = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})} \tag{5}$$

By using the average diameter value, the Brinell hardness can be calculated:

$$HB = \frac{2 \cdot 60}{\pi \cdot 2.5(2.5 - \sqrt{2.5^2 - 0.721^2})} = 150.2$$

Finally, to calculate the error of the Brinell test, the error of the diameter measurement must be calculated. By using Eq. (3), the following calculation is made:

$$\delta d = \sqrt{\left(\frac{\frac{2 \cdot 0.00786}{\sqrt{5}}}{2.5}\right)^2 + 0.01^2} = 0.1$$

Afterwards Eq. (2) can be used to calculate the error of the Brinell test measurements:

$$\Delta HB = 150.15(\sqrt{2} \cdot 0.2) = 15.02 \approx 20$$

Contributing to a final result of:

$$HB = (150.15 \pm 20)$$

5 Discussion

The primary goal of the experiment was to investigate the hardness of different metal samples using Vickers, Brinell, and Rockwell hardness testing methods. Particular attention was given to understanding the influence of quenching and plastic deformation on steel hardness. Additionally, the suitability, precision, and consistency of each method were evaluated.

5.1 Consistency of Results and Method Comparison

The obtained results, summarized in Table 9 below, demonstrate overall consistency across the methods when conversion relationships are taken into account.

Table 9: Overview of measured hardness values

Material	Vickers (HV)	Rockwell (HRB/HRC)	Brinell (HB)
$\text{Steel}_{\text{unhardened}}$	(156.1 ± 30)	(82 ± 1) HRB	-
Steel, hardened	(741.3 ± 20)	(63.2 ± 2) HRC	-
Brass	(166.3 ± 30)	(86.8 ± 1) HRB	(150.1 ± 20)
Tensile sample (original)	-	(82 ± 1) HRB	-
Tensile sample (drawn)	-	(85.6 ± 2) HRB	-

The results for the brass sample confirm mutual consistency among the three testing methods.The Vickers (166 ± 30) HV and Brinell (150 ± 20) HB HB values differ by 9.6%, which falls within the 12% tolerance permitted by ASTM E140 conversion tables [1]. The Rockwell B result (86.8 ± 1) HRB HRB further aligns with the expected range (80–90 HRB) for 166 HV, as confirmed by the ASTM E140 conversion chart. In the case of steel samples, the large disparity in hardness values between the hardened and unhardened C45 blocks validates the significant effect of quenching. Quenching transformed the steel's microstructure to martensite, which is much harder and more brittle [6]. This was reflected in the increase of the Vickers hardness from approximately 156 HV to 741 HV, and a corresponding shift from HRB 82 to HRC 63. These transitions align with the theoretical expectations and provided conversion tables [1].

The Rockwell B values for the tensile samples (original and drawn) also illustrate the phenomenon of work hardening. The drawn sample exhibited a hardness of 85.6 HRB compared to 82 HRB for the original, indicating an increase in strength due to dislocation multiplication during plastic deformation.

5.2 Accuracy and Precision of the Methods

Among the methods, Vickers showed the highest potential accuracy due to its diamond indenter and independence from applied load. However, its results also demonstrated the highest uncertainty, primarily due to the microscope's limited resolution and the squared dependence of the formula on diagonal length, amplifying any small error in measurement. By using a digital microscope, the precision of this test is limited by the scale of the diameter measurement.

The Brinell method, although robust and suited for heterogeneous materials like brass, showed a moderate error of ± 20. This is attributed to the difficulty in precisely measuring the indentation diameter and the need for surface preparation.

Rockwell tests proved the most practical and precise (± 1 to ± 2) due to their direct digital readings and minimal user interpretation [3]. They are thus particularly suitable for routine testing in industrial contexts.

5.3 Interpretation of Deviations

No significant discrepancies were observed among the methods when accounting for conversion and material suitability.

5.4 Answers to the questions

1. **Hardness–Tensile Strength Relation:**

   The approximate empirical formula is:

$$\sigma_{ts} \approx 3.45HV \tag{6}$$

2. **Why Not Start With Brinell or Rockwell B:**

   Brinell and Rockwell B are inappropriate for very hard materials. Starting with them may damage the steel indenter or yield no indentation. Vickers, with its diamond indenter, is safer for unknown hardness levels.

3. **Recommended Methods:**

   - Thin copper plates: Vickers — due to the small indentations and minimal load required.
   - Hardened steel in series production: Rockwell C — fast, repeatable, and directly readable.
   - Cast bronze bearing: Brinell — larger indenter averages out local inhomogeneities.

4. **Why So Many Hardness Methods:**

   Different materials and applications require different penetrative forces, sensitivities, and surface preparations. Brinell suits coarse materials, Vickers small or thin specimens, Rockwell provides fast results, and each method suits a specific industrial context.

5. **Rockwell Method for Brinell 175:**

   According to the conversion graph, a Brinell hardness of 175 corresponds to approximately 89.6 HRB. Thus, Rockwell B is appropriate.

6. **Why Not Indent Too Close:**

   A second indentation near a previous one affects the stress distribution, typically causing the material to appear softer (measured value too low) due to local work hardening and plastic deformation already induced.

7. **Hardness of Rubber – Shore Hardness:**

   The Shore durometer test uses a spring-loaded indenter to measure resistance to penetration. It differs fundamentally from metal hardness tests by being dynamic and dependent on elastic rather than plastic deformation [7].

6 Conclusion

The experiment confirmed the substantial effect of heat treatment on hardness, with quenched C45 steel exhibiting a hardness of (741 ± 20) HV compared to (156 ± 30) HV for unhardened steel. Rockwell tests provided the most repeatable results ($\pm$1–2) HRB/HRC, while Vickers and Brinell methods showed higher uncertainties due to measurement sensitivities. These findings highlight the need to align hardness testing methods with material properties:Vickers for precision on small features, Rockwell for rapid industrial use, and Brinell for coarse or inhomogeneous materials.

7 Bibliography

References

[1] *Standard Hardness Conversion Tables for Metals*, ASTM International, West Conshohocken, PA, 2023.

[2] *Standard Test Method for Brinell Hardness of Metallic Materials*, ASTM International, West Conshohocken, PA, 2023.

[3] *Standard Test Methods for Rockwell Hardness of Metallic Materials*, ASTM International, West Conshohocken, PA, 2023.

[4] J. Loeckx, “Hardness measurements,” KU Leuven, Lab Manual, 2024.

[5] L. Deneyer and J. Loeckx, “Uncertainty analysis,” KU Leuven, Lab Manual, 2024, 1st Semester.

[6] W. Dewulf, *Structure, Behaviour and Sustainability of Materials*, KU Leuven, 2023, course notes.

[7] *Standard Test Method for Rubber Property—Durometer Hardness*, ASTM International, West Conshohocken, PA, 2023.