# Evaluation of elastic recovery of metallic materials during determination of Rockwell hardness

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**Abstract**. This work aims to demonstrate that the conventional property of Rockwell hardness is related to the elastic and plastic contributions promoted by the indenter when pressed against the surface of a metallic material. It has been shown that Rockwell Hardness is associated with a permanent deformation that is guaranteed by maintaining the initial force during the execution of the method. This elastic contribution is part of the result, being able to concentrate up to 66.4% of the Rockwell Hardness value for a given scale. However, this measurable elastic contribution is usually neglected. The authors are convinced that this behavior of materials during Rockwell Hardness determination can serve as a parameter to infer or measure other mechanical properties of materials, such as resilience, tenacity and modulus of elasticity.

## 1. Introduction

Hardness can be described in a simplified way as a quantity associated with the mechanical resistance of all materials no matter if it is estimated by quantitative methods (indentation ones, the most used with metals, and rebound tests, commonly used with plastics and rubber) or qualitative methods (Mohs, scratching or cutting tests). This quantity is widely used for quality control in production lines and checking desired or designed properties in industries´ receiving sector of materials and raw materials, as well as in production lines, in steel, automotive, naval, aerospace, tubing, machines & tools, and oil & gas industries among other sectors [1-4].

The so-called Rockwell hardness was established in 1922 and the rules governing the test method for its determination are established in ASTM E18 (Standard test method for Rockwell hardness of metallic materials) [5] and in ISO 6508-1 (Metallic materials – Rockwell hardness test – Part 1: Test method) [6].

The method, show in Figure 1, for determining Rockwell hardness consists of applying a force through an indenter of specified size, shape and material to the surface of a test specimen at two levels of force under specified conditions. The initial force is applied and the initial indentation depth is measured, followed by the application and removal of an additional specified force, returning to the initial force. Thus, the Rockwell hardness is calculated from the final and initial depths and two constants N and S (which depend on the hardness range and scale), as shown in Equation 1 [6].

$$HR = N - \frac{h}{S} \quad (1)$$

Where:
HR – Rockwell hardness;
N – Constant that depends on the range of the hardness scale;
S – Constant that depends on the hardness scale;
h – Permanent indentation depth reached during the test in mm.

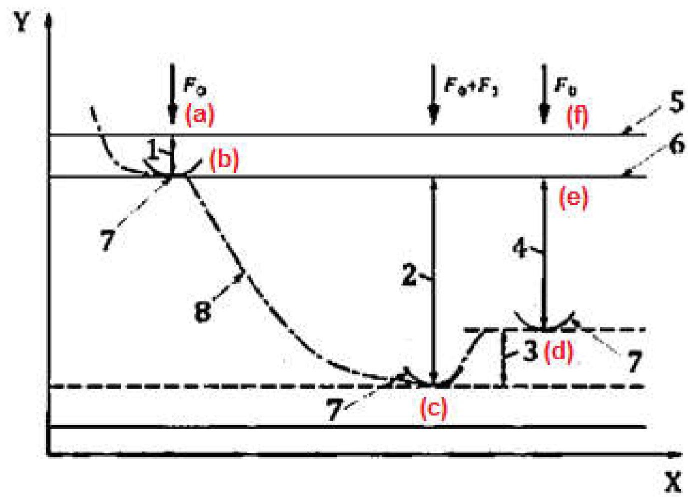


**Figure 1**. Rockwell principle diagram adapted from [6]

In Figure 1 the coordinates of the cartesian plane are X for time and Y for indenter position during the Rockwell hardness determination method. Point (a) is the point where the indenter touches the surface of the material, therefore, where the depth is to be considered zero, being the baseline plane 5. Point (b) is the depth of indentation due to the application of the initial force ($F_0$) and line segment 1 is equivalent to the value of the depth reached: it is where, locally, there was elastic deformation that comes to be added to the deformation due to material´s short, medium, and long distance internal residual stresses. Point (c) is the maximum indentation depth due to the application of the additional test force ($F_1$). The elastic deformation just after removing the additional test force ($F_1$) is related to point (d), which is the result of the negative deformation represented by segment 3. The straight line segment 4 means the permanent indentation depth (h) which is the point (e) in relation to plane 6 which is used as a reference to provide the Rockwell scale hardness value. Point (f) back to baseline plane 5 is associated with the sample surface plane. Point 7 refers to the outer envelope of the indenter tip (sphereconical tip for scales HRC and HR15N, and spherical one for HRB and HR15T) as well as curve 8 is the behavior of indentation depth over time [6 – 7].

Although not explicitly covered by the indentation hardness standards, the determination of the hardness property is related to the interaction of elastic deformation (at the contact point of the indenter with the material) with the residual stresses of the volume of the hardness block – here called together as "elastic recovery" –, both in the application of the initial and additional forces and in the removal of these forces. The permanent deformation ($h$) that is used in equation 1 is obtained by removing the additional force and maintaining the initial force, until the value of that initial force is stabilized. Table 1 presents the Rockwell hardness scales that were studied in this work to evaluate the elastic recovery of metallic materials during the Rockwell hardness method [6 – 9].

**Table 1**. Rockwell scales evaluated during this work

| Rockwell Hardness Scale | Symbol of hardness | Indenter type | Initial force, $F_0$ [N] | Total force, F [N] | Scale constant, *S* [mm] | Full range constant, *N* [N] | Minimum value [HR] | Maximum value [HR] |
|---|---|---|---|---|---|---|---|---|
| B | HRB | Ball of 1.5875 mm | 98.07 | 980.7 | 0.002 | 130 | 10 | 100 |
| C | HRC | Diamond Cone | 98.07 | 1471 | 0.002 | 100 | 20 | 70 |

The choice of these Rockwell hardness scales presented in Table 1 for carrying out the work was based on the variability of the values of initial force and total force, indenter type used and amplitude of the depth of indentation evaluated during the execution of the method [6].

The objective of this work is to estimate and compare the elastic recoveries still present in permanent deformation, when the additional force ($F_1$) is withdrawn and the initial force ($F_0$) is maintained, during the performance of the hardness scales HRB and HRC.

## 2. Materials and Methods

To carry out the tests with metrological reliability, the Inmetro's Hardness Primary Standardization Machine was used, in which both the Rockwell hardness scale and the Brinell and Vickers scales can be performed. Figure 2 shows an image of the Hardness Primary Standardization Machine.

**Figure 2**. Inmetro's Hardness Primary Standardization Machine.

The Hardness Primary Standardization Machine provided the results of time, force and depth during all tests carried out on the materials analyzed in this work. The parameters extracted from the calibrations of two Rockwell hardness reference blocks were analyzed. In other words, data from the following calibrations were evaluated: a Rockwell HRB Hardness Reference Block and a Rockwell HRC Hardness Reference Block. All Rockwell hardness reference blocks were in accordance with ISO 6508-3:2016 requirements [9].

Below are the equations that, together with the calibration data, made up the process of evaluating relevant parameters and treating the data reported in this work. Equation 2 shows the percentage of elastic recovery after the removal of the additional force ($F_1$) that is the ratio between the length measurement of the elastic recovery at the surface of the hardness reference block due to the withdrawal of $F_1$ and the maximum depth reached of the indenter after applying the total force ($F_0 + F_1$) used to perform the Rockwell hardness scale. Equation 3 is the result of complementarity between plastic and elastic contributions during the Rockwell hardness determination method. The percentage of elastic recovery retained during the maintenance of the initial force ($F_0$) will be calculated from equation 4. From the analysis of these data, the results and discussions are presented below.

$$\%\, recovery\ F_1\ removal = 100 \cdot \left(\frac{recovery\ length\ by\ F_1\ removal}{depth\ after\ applying\ total\ force}\right) \quad (2)$$

$$\%\, permanent\ depth\ after\ F_1\ removal = 100 - \%\, recovery\ \ by\ F_1\ removal \quad (3)$$

$$\%\, recovery\ retained\ \ of\ F_0\ maintenance = 100 \cdot \left(\frac{recovery\ length\ by\ F_0\ removal}{depth\ after\ applying\ total\ force}\right) \quad (4)$$

## 3. Results and discussion

### *3.1 Results for Rockwell B Hardness*

Rockwell B Hardness (HRB) is determined from the depth left by a spherical tungsten carbide (WC) indenter with a tip diameter of 1.5875 mm. Figure 3 illustrates the indentation depth results (in millimeters) as a function of the elapsed time of the test (in seconds).

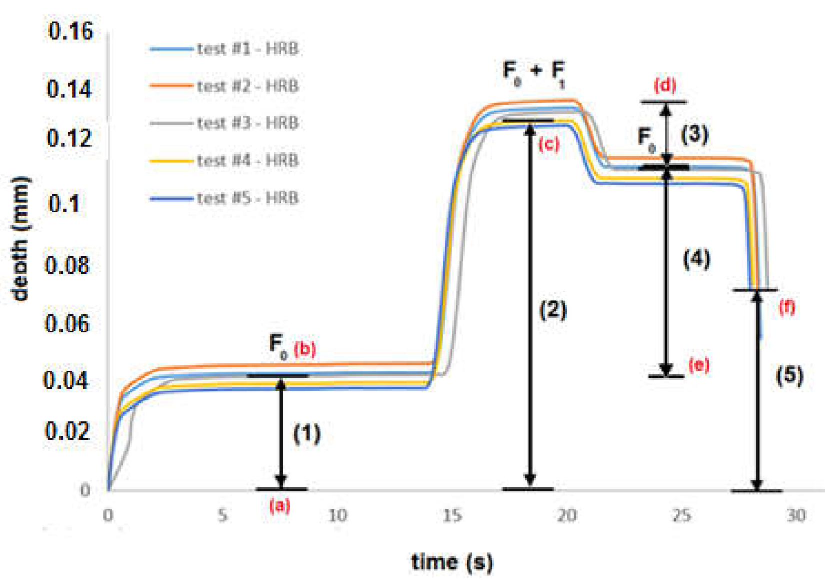


**Figure 3**. Indentation depth as a function of time during 5 HRB tests

In the method for determining Rockwell B hardness, an initial force of 98.07 N ($F_0$) is applied, which must occur within a maximum period of 2 s. The surface of the material, before contact with the indenter is represented by point (a). When the initial force value is reached, it must be maintained between 1 and 5 s, which is represented by point (b). Within this time interval, the depth of indentation in segment (1) is measured, which position was reached by the indenter after applying the initial force ($F_0$). Then the additional force of 882.63 N ($F_1$) is applied in the period from 1 to 8 s. Subsequently, the total force of 980.7 N ($F_0 + F_1$) is maintained applied for a minimum of 2 s and a maximum of 8 s that is associated with point (c). In this time interval, the total indenter depth represented in segment (2) is measured and recorded. Then there is an unloading of the additional force ($F_1$), returning to the initial force value ($F_0$) represented at point (d), where some elastic recovery associated with segment (3) occurs. After stabilizing the depth at point (e), the depth referring to the length of the segment (4) is measured in millimeters and this value will be used to determine the Rockwell hardness. Point (f) is the final position of the indenter after withdrawal of the initial force at the end of the test, segment (5) being the depth after unloading of $F_0$. From the analysis of Figure 3, it is possible to report the data as presented in Table 2.

**Table 2**. Mean values found by the graphical analysis of data in Figure 3

| # | Properties | [mm] |
|---|---|---|
| 1 | Average depth at $F_0$ (segment 1 in Figure 3) | 0.039706 |
| 2 | Average depth at total force $F_0 + F_1$ (segment 2 in Figure 3) | 0.131933 |
| 3 | Average depth after $F_1$ withdrawal (segment 4 in Figure 3) | 0.071924 |
| 4 | Mean elastic recovery after $F_1$ removal (segment 3 in Figure 3) | 0.020303 |
| 5 | Mean elastic recovery after $F_0$ withdrawal | 0.064907 |

From the values in Table 2 and with the use of equations (2), (3) and (4) the percentage values of elastic recovery after removal of the additional force, permanent deformation after removal of the additional force and the recovery retained or stored in the material by maintaining the initial force at the time of determining the depth (which is used as a reference for calculating the HRB hardness value). The average value in HRB of the hardness reference material can be calculated by the values shown in Table 1 and 2 and by using equation (1), as shown in Table 3.

**Table 3**. Average values of % elastic recovery and permanent deformation for the HRB hardness method

| # | Properties | Values |
|---|---|---|
| 1 | % elastic recovery (partial) after removal of $F_1$ (in relation to segment 3 in Figure 3) | 22.0 |
| 2 | % permanent deformation (partial) after removal of $F_1$ (in relation to segment 4 in Figure 3) | 78.0 |
| 3 | % elastic recovery stored by maintaining $F_0$ (segment 4 in Figure 3) | 48.4 |
| 4 | % total elastic recovery | 49.2 |
| 5 | % total plastic deformation | 50.8 |
| 6 | Average hardness value/HRB | 94.0 |
| 7 | HRB hardness minus the elastic recovery stored by maintaining $F_0$ | 83.9 |
| 8 | Contribution to HRB hardness of elastic recovery stored by maintaining $F_0$ | 10.1 |

As seen in Table 3, for a material with 94.0 HRB hardness, it is possible to verify that 48.4% of elastic deformation is present when the nominal hardness value is determined. That is, it is possible to state that during the implementation of the Rockwell B hardness method there is still a recovery contribution in relation to the permanent deformation after the removal of the additional force, which is sustained within the material by maintaining the initial force. In hardness values, this contribution of the elastic recovery retained in the material by maintaining the initial force resulted in a difference of 10.1 HRB in relation to the material hardness value (94 HRB). This difference in HRB hardness values represented 10.7% of the total.

*3.2 Results for Rockwell C Hardness*

Rockwell C Hardness (HRC) is determined from the depth left by a spherical diamond indenter with a tip radius of around 200 µm. Figure 4 illustrates the indentation depth results (in millimeters) as a function of the elapsed time of the test (in seconds).

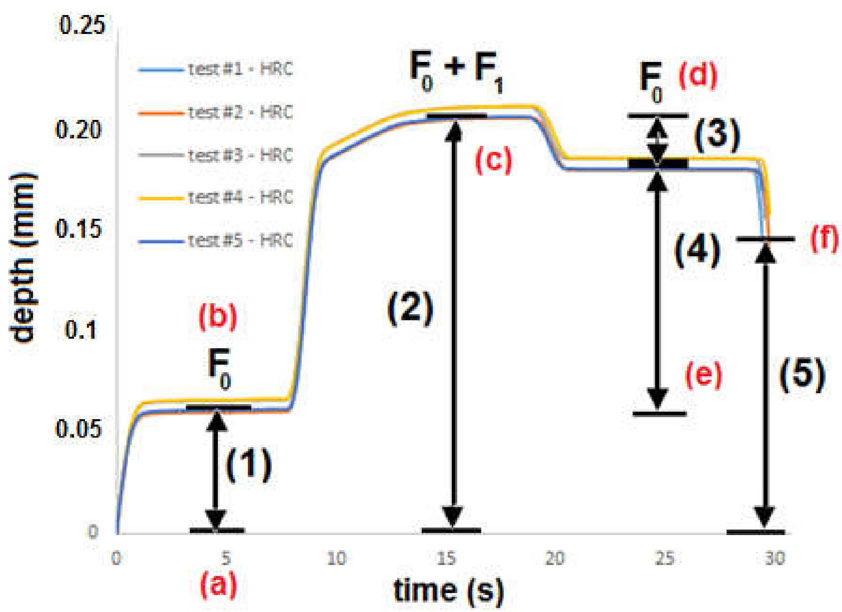


**Figure 4**. Indentation depth as a function of time during 5 HRC tests

In the method for determining the Rockwell C hardness, an initial force of 98.07 N ($F_0$) is applied, which must occur within a maximum period of 2 s. When the initial force value is reached, it must be maintained between 1 to 5 s. Within this time interval, the depth in segment (1) is measured, which the position is reached by the indenter after the application of $F_0$. Then the additional force of 1372.93 N ($F_1$) is applied between 1 and 8 s. The total force of 1471 N ($F_0 + F_1$) is then kept applied for a minimum of 2 s and a maximum of 8 s. In this time interval the total depth of the indenter in segment (2) is measured and recorded. Then there is an unloading of the additional force ($F_1$), until the return to the initial force intensity ($F_0$), where elastic recovery occurs in segment (3), and, after stabilization, the depth in segment (4) is measured and the its respective value in millimeters will be used to determine the Rockwell C hardness of the tested reference material. Segment (5) is the final position of the indenter after withdrawal of the initial force at the end of the test. From the analysis of Figure 4, it is possible to relate the data as presented in Table 4.

**Table 4**. Mean values found by the graphical analysis of the data in Figure 3

| # | Properties | [mm] |
|---|---|---|
| 1 | Average depth at $F_0$ (segment 1 in Figure 4) | 0.063547 |
| 2 | Average depth at total force $F_0 + F_1$ (segment 2 in Figure 4) | 0.209361 |
| 3 | Average depth after $F_1$ removal (segment 4 in Figure 4) | 0.119814 |
| 4 | Mean elastic recovery after $F_1$ removal (segment 3 in Figure 4) | 0.026000 |
| 5 | Mean elastic recovery after $F_0$ removal | 0.061100 |

Based on the values in Table 4 and using equations (2), (3) and (4), the percentage values of elastic recovery after removal of the additional force, permanent deformation after removal of the additional force and recovery retained or stored in the material by maintaining the initial force at the time of determining the depth (which is used as a reference for calculating the HRC hardness value). The average value in HRC of the hardness reference material can be calculated by the values shown in Tables 1 and 2 and by using equation (1), as shown in Table 5.

**Table 5**. Average values of % elastic recovery and permanent deformation for the HRC hardness method

| # | Properties | Values |
|---|---|---|
| 1 | % elastic recovery (partial) after removal of $F_1$ (in relation to segment 3 in Figure 4) | 17.8 |
| 2 | % permanent deformation (partial) after removal of $F_1$ (in relation to segment 4 in Figure 4) | 82.8 |
| 3 | % elastic recovery stored by maintaining $F_0$ (segment 4 in Figure 4) | 24.1 |
| 4 | % total elastic recovery | 29.2 |
| 5 | % total plastic deformation | 70.8 |
| 6 | Average hardness value/HRC | 40.1 |
| 7 | HRC hardness minus the elastic recovery stored by maintaining $F_0$ | 27.1 |
| 8 | Contribution to HRB hardness of elastic recovery stored by maintaining $F_0$ | 13.0 |

For a material with 40.1 HRC hardness, it can be seen that 24.1% of elastic deformation is present at the time of determining the nominal hardness value. In this way, it is possible to consider that during the implementation of the Rockwell C hardness method there is still a contribution of recovery in relation to the permanent deformation after the removal of the additional force that is kept stored in the reference material by maintaining the initial force. In hardness value, this contribution of elastic recovery retained in the material by the initial force represents a difference of 13.0 HRC in relation to the hardness value in the material. This difference in HRC hardness values represents 32.4% of the total.

*3.3 Analysis of the impact of stored elastic recovery on the Rockwell Hardness of Metallic Materials*

The HRB scale showed a heterogeneous behavior in relation to the distribution of elastic and plastic contributions present in the determination of the hardness value of the metallic material when compared to the HRC scale (Figure 6) as can be seen in Figure 5.

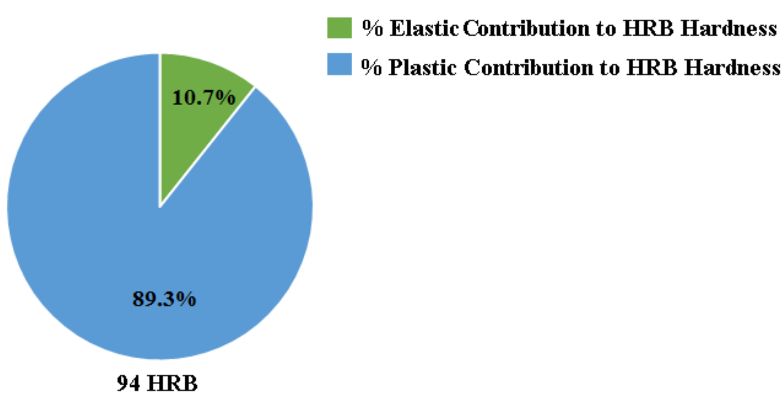


**Figure 5.** Elastic and plastic contributions in relation to the HRB hardness value

The contribution of plastic deformation corresponded to 89.3% of the hardness value for the HRB scale and its elastic portion was the lowest among all the hardness scales analyzed in this work, corresponding to only 10.7%. For the HRC scale, an increase in the elastic contribution was observed to account for the HRC value of the metallic material tested, as shown in Figure 6, below.

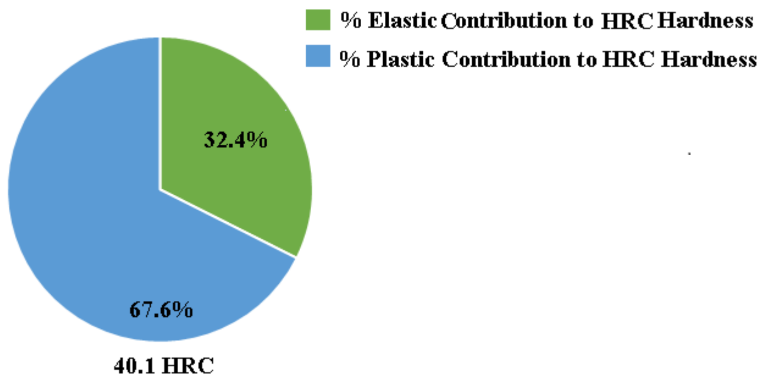


**Figure 6**. Elastic and plastic contributions to the HRC hardness value

For the HRC scale, an increase in the contribution of elastic deformation was observed compared to the HRC scale, reaching 32.4% of the hardness value of the metallic material tested.

## 4. Conclusion

This work was able to demonstrate that Rockwell hardness is associated with a permanent deformation that is guaranteed by maintaining the initial force. Effectively, it can be shown that there is a measurable elastic contribution that is part of the result and that contributes significantly to the Rockwell hardness value in Rockwell B and C hardness scales. The contribution of plastic deformation corresponded to 89.3% of the hardness value for the HRB scale and its elastic portion was the lowest among all the hardness scales analyzed in this work, corresponding to only 10.7%. For the HRC scale, an increase in the elastic contribution was observed to account for the HRC value of the metallic material tested. The authors believe that future studies shall demonstrate that this elastic contribution, which is normally neglected, can serve as a parameter to infer or measure other mechanical properties of metallic materials such as resilience, tenacity, modulus of elasticity, among others.

## References

[1] TABOR, D., The Hardness of Metals, 1951, 1ST Edition, New York, Oxford;
[2] SMITH W.F., HASHEMI, J., Foundations of Materials Science and Engineering, 2009, 5Th Edition, McGraw Hill;
[3] BEER, F. P. et al., Mechanics of Materials, 2014, 7th Edition, McGraw Hill;
[4] SOUZA, S. A., Ensaios Mecânicos de Materiais Metálicos, 1982, 12ª Edição, São Paulo: Blücher;
[5] ASTM E18-22, Standard Test Methods for Rockwell Hardness of Metallic Materials;
[6] ISO 6508-1:2016, Metallic Materials – Rockwell hardness test – Part 1: Test method;
[7] EURAMET/cg-16/v.01, Calibration Guide - Guidelines on the Estimation of Uncertainty in Hardness Measurements, 2007, EURAMET, Braunschweig, Germany.
[8] ISO 6508-2:2015, Metallic Materials – Rockwell hardness test – Part 2: Verification and calibration of testing machines and indenters;
[9] ISO 6508-3: 2015, Metallic Materials – Rockwell hardness test – Part 3: Calibration of reference blocks;