Determination of test cycle sensitivity coefficients for the Rockwell HRA hardness scale

S Low1 and R R Machado2

1 National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA
2 Instituto Nacional de Metrologia, Qualidade e Tecnologia (INMETRO), Duque de Caxias, RJ, Brazil

E-mail: samuel.low@nist.gov

Abstract. This report describes investigations carried out to determine test cycle sensitivity coefficients for the Rockwell HRA hardness scale. Sensitivity coefficients were determined for the preliminary-force, total-force and recovery-force dwell times. The work was carried out in 2017 at the National Institute of Standards and Technology (NIST) in Gaithersburg, USA.

1. Introduction

Rockwell hardness is an ordinal quantity measurement and is therefore dependent on a defined test method. In today’s international commerce, Rockwell hardness testing is almost exclusively conducted in compliance with the test methods specified by ASTM-International (test method ASTM E18) [1] or the International Organization for Standardization (test method ISO 6508) [2]. These test methods specify requirements for the significant parameters of the Rockwell hardness test, which can be divided into three test parameter categories: force, length and time. Since ASTM and ISO test methods are primarily intended for industrial use, the test parameters are specified to be within ranges of values to accommodate the different testing needs and types of Rockwell testing machines.

Within the structure of the International Committee of Weights and Measures (CIPM) is the Consultative Committee for Mass and Related Quantities (CCM) [3], and within the CCM is the Working Group on Hardness (CCM-WGH). The Working Group on Hardness members are the world’s National Metrology Institutes (NMI) that standardize hardness measurement. The CCM-WGH provides a technical-diplomatic framework in which hardness influence parameters can be examined. The intent is to develop improved international definitions of the hardness tests for use by NMIs to reduce the measurement differences at the highest national level. The CCM-WGH defines each parameter to have a specific value and not ranges of values as is practiced by the ASTM or ISO test methods. It is critical that the CCM-WGH understands how each test parameter affects the hardness result before choosing the definition values for the various test parameters. As of now, the Rockwell hardness A scale (HRA), which is used to test both ferrous and non-ferrous metals, has yet to be defined by the CCM-WGH.

This report describes investigations carried out in 2017 at NIST to determine the HRA test cycle sensitivity coefficients for the preliminary-force, total-force and recovery-force dwell times (see

1 National Institute of Standards and Technology (NIST), 100 Bureau Drive, Stop 8553, Gaithersburg, MD, 20899, USA, samuel.low@nist.gov
This information can assist the CCM-WGH in defining the HRA hardness scale, and for calculating HRA measurement uncertainty.

Figure 1 illustrates the HRA test cycle, where the variation of the applied force over the test time is shown at the top portion of the figure, and the corresponding indentation behaviour is shown below. The Rockwell HRA hardness test applies two levels of force to the indenter and measures the indentation depth twice during the test cycle. The two measurements of the indentation depth are indicated by red arrows. A Rockwell spheroconical diamond indenter is brought into contact with the test sample and a preliminary-force $F_0$ of 98.07 N (10 kgf) is applied. After maintaining the applied force for a specific time, defined as the preliminary-force dwell (or duration) time, the initial measurement of indentation depth is made. The applied force is increased to the total-force $F$ of 588.4 N (60 kgf), and is again maintained for a specific time, defined as the total-force dwell (or duration) time. The force is then decreased to the force $F_0$ of 98.07 N (10 kgf) and maintained for a specific time, defined as the recovery-force dwell (or duration) time after which the final depth measurement is made. The indenter is then removed from the test sample. The HRA value is calculated from the difference between the initial and final depth measurements ($\Delta d$ in figure 1) as given in equation 1, where $\Delta d$ is in mm.

$$HRA = 100 - \frac{\Delta d}{0.002} \quad (1)$$

Each of the three dwell times has the potential of influencing the hardness result due to indentation creep or material recovery occurring during the force dwell times. In other words, the depth of the indenter is continually changing while the force is held constant. Greatly expanded views of the indentation depth during the three dwell times are given at the bottom of figure 1, illustrating the indentation creep and material recovery that is occurring. Previous studies [4] have shown that the magnitude of depth change during the dwell times can be directly correlated to a change in hardness value.

The effect of the three dwell times, varying one at a time and keeping all else constant, can be realized from figure 1. As the preliminary-force dwell time becomes longer, the indenter creeps deeper into the material thereby increasing the initial depth measurement. The effect is to reduce $\Delta d$ and thus increase the hardness value. The effect of the total-force dwell time becoming longer is that the indenter creeps deeper into the material, causing the starting depth at which the indenter begins the unloading portion of the test cycle to be deeper. This translates into the start of the recovery-force dwell time also being deeper, which increases $\Delta d$, and thus decreases the hardness value. Lastly, during the recovery dwell time, the material surrounding the indenter experiences primarily elastic recovery, although with a small reverse-plasticity component, and the indentation depth decreases, reducing $\Delta d$, and thus increasing the hardness value.

A fourth test parameter, the additional force application time, when the force increases from the preliminary force to the total force, can also influence the HRA result. This parameter was not investigated in this study.

![Figure 1. Schematic of the HRA test illustrating the force application and corresponding indentation depth during the test cycle. Expanded views are displayed of the material creep and recovery occurring during force dwell times.](image_url)
2. Experimental methodology
To examine the effect of the preliminary-force, total-force and recovery-force dwell times, HRA hardness tests were conducted by varying each of the three dwell times across the ranges of test cycle times specified in the test methods [1, 2]. The tests were made on uncalibrated reference blocks at six levels of hardness using the NIST Rockwell hardness standardizing machine [5]. Three hardness levels (nominally 32 HRA, 40 HRA and 51 HRA) were tested using brass reference blocks, and three hardness levels (nominally 63 HRA, 73 HRA and 83 HRA) were tested using steel reference blocks. The applied force and indentation depth were recorded during the indentation process so that the indentation changes during the dwell times could be observed.

3. Analysis
Figures 2, 3 and 4 show the extent of indenter change during the preliminary-force, total-force and recovery-force dwell times, respectively. Since the HRA calculation is based directly on this depth of indentation (equation 1), the units of the vertical axis showing indenter depth have been converted to a change in HRA units by simply dividing the indenter depth change in mm by 0.002 mm per HRA unit. HRA hardness tests with very long dwell times were made to obtain the extended dwell time data in these figures. Each data line is a fit to the average data from four individual measurements. The solid data curves are steel material test results (63, 73 and 83 HRA), and the dashed data curves are the brass material results (32, 40 and 51 HRA).

To confirm that the test depth data represents the actual change in hardness due to the dwell times, the HRA measurements that were made at specific dwell times were plotted over the depth data. An example is given in figure 5. The error bars represent 1-σ standard deviation of 4 measurement results. Due to block non-uniformity and test repeatability, particularly for the brass material tests, some individual test results could not perfectly reflect the very small changes in HRA results, however, the data do not contradict the results from the depth data.

The CCM-WGH definition of the Rockwell hardness C scale (HRC) defines the values of the preliminary-force, total-force and recovery-force dwell times as 3 s, 5 s and 4 s, respectively. NMIs have often used these HRC scale defined times for standardizing the other Rockwell scales as well.
It would be practical and convenient if the HRA test method could be defined with these values, but the sensitivity coefficients would have to be small enough for this to be an appropriate decision. By differentiating the data curves presented in figures 2 to 4, the sensitivity coefficients (HRA/s) can be determined for any dwell time. Table 1 gives the calculated sensitivity coefficients for the above stated dwell times. The uncertainties were calculated as the standard deviation of the mean of the four measurements made to determine each sensitivity coefficient value. These values are of the same magnitude as reported previously by the National Physical Laboratory in the UK for the HRA steel levels [6], the differences likely due to the NPL data being based only on HRA values and not on indentation depth changes. It is interesting to note that the HRA sensitivity coefficients when testing brass are significantly smaller than for testing steel using these dwell times.

4. Conclusion

This study has determined sensitivity coefficient values for six levels of the Rockwell HRA scale, including when testing brass and steel materials. The sensitivity coefficients are sufficiently small for the preliminary-force, total-force and recovery-force dwell times of 3 s, 5 s and 4 s, respectively, that the CCM-WGH can be confident that these dwell times are appropriate for an international definition.

5. References

[1] ASTM E18-17c1 2017 Standard Test Methods for Rockwell Hardness of Metallic Materials (West Conshohocken, PA: ASTM International)
[2] ISO 6508-1:2016 Metallic Materials—Rockwell Hardness Test -- Part 1: Test method (Geneva: International Organization for Standardization)
[3] www.bipm.org/wg/CCM/CCM-WGH/Allowed/International definitions/HRC_definition.pdf
[4] Low S and Fink J 2003 Effects of bending in brass Rockwell B scale test blocks Proc. XVII IMEKO World Congress on Metrology in the 3rd Millennium (Dubrovnik, Croatia June 2003)
[5] Low S, Gettings R, Liggett W and Song J, Rockwell hardness - a method-dependent standard reference material, Proc. NCSL Workshop and Symposium (Charlotte, NC, July 1999)
[6] Brice L, Low S and Jiggett R 2006 Determination of sensitivity coefficients for Rockwell hardness scales HR15N, HR30N and HRA Proc. XVIII IMEKO World Congress on Metrology for a Sustainable Development (Rio de Janeiro, Brazil, September 2006)

Table 1: HRA sensitivity coefficients at specific values of dwell times.

| Material | Nominal Hardness (HRA) | Sensitivity Coefficients for the Preliminary-Force 3 s Dwell Time (HRA/s) | Sensitivity Coefficients for the Total-Force 5 s Dwell Time (HRA/s) | Sensitivity Coefficients for the Recovery-Force 4 s Dwell Time (HRA/s) |
|----------|-------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Brass    | 32                      | 0.005 ± 0.000 09                                | -0.004 ± 0.000 04                               | 0.001 ± 0.000 05                                |
| Brass    | 40                      | 0.005 ± 0.000 13                                | -0.005 ± 0.000 03                               | 0.001 ± 0.000 14                                |
| Brass    | 51                      | 0.006 ± 0.000 07                                | -0.007 ± 0.000 06                               | 0.002 ± 0.000 06                                |
| Steel    | 63                      | 0.025 ± 0.000 33                                | -0.040 ± 0.000 28                               | 0.001 ± 0.000 04                                |
| Steel    | 73                      | 0.010 ± 0.000 23                                | -0.022 ± 0.000 14                               | 0.002 ± 0.000 07                                |
| Steel    | 83                      | 0.005 ± 0.000 05                                | -0.012 ± 0.000 11                               | 0.003 ± 0.000 15                                |

Figure 5: Change in 83 HRA (steel) due to indentation creep during the total-force dwell time, overlaid with test data made using 2 s, 4 s, 5 s, 6 s and 10 s dwell times.