Determination of test cycle sensitivity coefficients for the Rockwell HR45N hardness scale

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Abstract. This article describes work carried out to determine test cycle sensitivity coefficients for the Rockwell HR45N 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

There is an ongoing international effort within the Consultative Committee for Mass and Related Quantities - Working Group on Hardness (CCM-WGH) to reduce measurement differences between National Metrology Institutes (NMIs) that standardize hardness reference blocks [1]. One of the limitations of hardness quantity measurements is that the conventional measurement is dependent on a test method defined by international standards, e.g. ISO [2] and ASTM [3]. These test methods specify the test parameters to be within ranges of values to accommodate the different testing needs and types of Rockwell testing machines. These definitions are not sufficiently unambiguous for use by the world’s National Metrology Institutes that standardize hardness measurement, so NMIs comply with definitions developed by the CCM-WGH. The CCM-WGH defines each parameter to have a specific value rather than ranges of values as specified by ISO and ASTM test methods. Consequently, the CCM-WGH must understand how each test parameter affects the hardness result before choosing the definition values for the various test parameters.

Bearing this in mind, the focus of this work was to investigate the Rockwell HR45N hardness scale to determine the effect of certain test-cycle parameters on the measurement results. Experiments were conducted in 2017 at NIST to determine the sensitivity coefficients for the parts of the test-cycle in which the force is held constant, namely the preliminary-force, total-force and recovery-force dwell (or duration) times. This information can be used to assist the CCM-WGH in defining the HR45N scale, and for calculating HR45N measurement uncertainty.

2. Rockwell HR45N test

The Rockwell HR45N test is known as a Rockwell superficial hardness test that differs from regular Rockwell tests, such as the HRA and HRC scales, primarily because of using lower applied forces. Figure 1 illustrates the HR45N test cycle, where the variation of the applied force over the test cycle is...
shown at the top portion of this figure, and the corresponding indentation behaviour is shown below. The Rockwell HR45N hardness test applies two levels of force to the indenter and measures the indentation depth two times during the test cycle. The two measurements of the indentation depth occur at the test-cycle times indicated by the red arrows. A Rockwell sphericonical diamond indenter is brought into contact with the test sample and a preliminary-force $F_0$ of 29.42 N (3 kgf) is applied. After maintaining the applied force for a specific time, known 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 441.3 N (45 kgf), and is again maintained for a specific time, known as the total-force dwell (or duration) time. The force is then returned to the force $F_0$ of 29.42 N (3 kgf) and maintained for a specific time, known 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 HR45N 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.

$$HR45N = 100 - \frac{\Delta d}{0.001}$$

### 3. Experimental methodology

To examine the effect of the preliminary-force, total-force and recovery-force dwell times, HR45N hardness tests were conducted by varying each of the three dwell times across the ranges of test cycle times specified in the test methods [2, 3]. It is important to point out that, while testing one specific parameter, all other dwell times were kept constant at preliminary-force: 3 s, total force: 5 s and recovery-force: 4 s. The tolerance ranges specified by the international standards are as follows:

- **Preliminary force dwell time**
  - ISO: (Calibration standard): $3 \pm 1$ s
  - ASTM: (Testing standard): 0.1 s to 4.0 s; (Calibration standard): $3 \pm 1$ s
- **Total force dwell time**
  - ISO (Calibration standard): $5 \pm 1$ s
  - ASTM: (Testing standard): 2.0 s to 6.0 s; (Calibration standard): $5 \pm 1$ s
- **Recovery force dwell time**
  - ISO (Calibration standard): $4 \pm 1$ s,
  - ASTM: (Testing standard): 0.2 s to 5.0 s; (Calibration standard): $4 \pm 1$ s

The test force dwell times carried out in this work were as follows:

- Preliminary force dwell time: (1, 1.5, 2, 3, 4, 6, 8 and 30) s
- Total force dwell time: (2, 4, 5, 6, 10, 15 and 30) s
- Recovery force dwell time: (0.5, 1, 3, 4, 5, 8 and 30) s
The HR45N tests were made on uncalibrated steel reference blocks at three levels of hardness (nominally 25 HR45N, 49 HR45N and 70 HR45N) using the NIST Rockwell hardness standardizing machine [4]. The applied force and indentation depth were recorded during the indentation process so that indentation changes during the dwell times could be observed.

4. Analysis

Figure 2 shows the extent of indenter change during the total-force dwell time [scaled to the left vertical-axis, indicated by the lines] and the preliminary-force and recovery-force dwell times [scaled to the right vertical-axis, where the preliminary-force is indicated by the bigger dashes and the recovery-force is indicated by the smaller dashes]. Since the HR45N calculation is based directly on this depth of indentation per equation (1), the units of the vertical axes showing indenter depth have been converted to a change in HR45N units by simply dividing the indenter depth change in mm by 0.001 mm/HR45N unit. Each data line is a fit to the average data from four individual measurements. In general, for the HR45N hardness ranges, the hardness change due to indentation creep and indentation recovery was more pronounced during the total-force dwell time, followed by the preliminary-force dwell time, with smaller changes for the recovery-force dwell time. The figure also show that the rates of changing were always faster during short dwell times.

To confirm that the indentation depth data represents the actual change in hardness due to the dwell times, the HR45N measurements that were made at specific dwell times were plotted over the depth data. Figures 3, 4 and 5 illustrate the change in hardness values during the preliminary-force, total-force and recovery-dwell times, respectively. Each figure shows four hardness change curves based on indentation data for four individual measurements, indicated by the different dot colors. The error bars represent 1-σ standard deviation of four HR45N measurement results.
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 convenient if the HR45N test method could be defined with these values, but the sensitivity would have to be low enough for this to be an appropriate decision. By differentiating the data curves presented in figure 2, the sensitivity coefficients (HR45N/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.

Previous work at NIST [5] analysed the dwell time effects of the Rockwell HR15N and HR30N hardness scales using a similar methodology, but reported the sensitivity coefficients for ranges of times. This sensitivity coefficient data has been re-analysed for specific dwell times as was done above for the HR45N scale, and is given in table 2. These values differ in that they are based on only one data curve, rather than the average of four data curves; however, the uncertainties would be expected to be of the same magnitude as the HR45N results of this reported study.

Table 1: HR45N sensitivity coefficients at specific values of dwell times.

| Material | Nominal Hardness (HR45N) | Sensitivity Coefficients for the Preliminary-Force 3 s Dwell Time (HR45N/s) | Sensitivity Coefficients for the Total-Force 5 s Dwell Time (HR45N/s) | Sensitivity Coefficients for the Recovery-Force 4 s Dwell Time (HR45N/s) |
|----------|--------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------|
| Steel 25 | 1.50E-02 ± 2.10E-04      | -7.70E-02 ± 1.20E-04                                                         | 4.00E-03 ± 1.40E-04                                                 |
| Steel 49 | 7.00E-03 ± 1.70E-04      | -3.70E-02 ± 6.60E-04                                                         | 5.00E-03 ± 1.00E-04                                                 |
| Steel 70 | 2.00E-03 ± 3.30E-04      | -2.20E-02 ± 2.70E-04                                                         | 4.00E-03 ± 1.40E-04                                                 |

Table 2: HR15N and HR30N sensitivity coefficients at specific values of dwell times.

| Nominal Hardness (HR15N) | Preliminary Force: 3 s (HR15N/s) | Total-Force: 5 s (HR15N/s) | Recovery-Force: 4 s (HR15N/s) | Nominal Hardness (HR30N) | Preliminary Force: 3 s (HR30N/s) | Total-Force: 5 s (HR30N/s) | Recovery-Force: 4 s (HR30N/s) |
|--------------------------|-----------------------------------|-----------------------------|-------------------------------|--------------------------|-----------------------------------|-----------------------------|-------------------------------|
| 72                       | 1.60E-02                          | -3.80E-02                   | 1.00E-03                      | 45                       | 3.70E-02                          | -5.50E-02                   | 4.00E-03                      |
| 83                       | 6.00E-03                          | -2.00E-02                   | 1.00E-03                      | 64                       | 1.20E-02                          | -3.10E-02                   | 4.00E-03                      |
| 91                       | 4.00E-03                          | -9.00E-03                   | 2.00E-03                      | 79                       | 6.00E-03                          | -1.80E-02                   | 5.00E-03                      |

5. Conclusion
This study has determined sensitivity coefficient values for three levels of the Rockwell HR45N scale. 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, so that the CCM-WGH can be confident that these dwell times are appropriate for an international definition. Re-examination of previous studies [5] of the HR 15N and HR30N scales show that the preliminary-force, total-force and recovery-force dwell times of 3 s, 5 s and 4 s are also appropriate for international definitions of these scales.

6. References
[1] https://www.bipm.org/en/committees/cc/wg/ccm-wgh.html
[2] ISO 6508-1:2016 Metallic Materials – Rockwell Hardness Test – Part 1: Test method (Geneva: International Organization for Standardization)
[3] ASTM E18-17 2017 Standard Test Methods for Rockwell Hardness of Metallic Materials (West Conshohocken, PA: ASTM International)
[4] 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)
[5] Brice L, Low S and Jiggetts 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)