Study of Improved National Primary Standard Machine on Rockwell and Superficial Rockwell Scales

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Abstract. The present article describes the study of the national primary standard machine on Rockwell and Superficial Rockwell hardness scales conducted with the aim of reducing the expanded measurement uncertainty. The authors of the article studied all the components of the hardness measurement uncertainty budget on Rockwell and Superficial Rockwell scales. Generally, sensitivity coefficients for the calculation of the expanded measurement uncertainty were determined experimentally. The results of the conducted research lead to the conclusion that the expanded hardness measurement uncertainty on Rockwell and Superficial Rockwell scales has been reduced.

1. Introduction
The Russian national primary standard machine on Rockwell and Superficial Rockwell scales was improved in 2017. The improvement included the replacement of the deadweight device, the system of Rockwell indenter penetration depth measurement. The primary standard machine is set on a vibro-isolated foundation, which minimizes the influence of vibrations on measurements. The temperature and humidity are kept constant in the room where the standard machine is installed. Rockwell and Superficial Rockwell scales are reproduced in compliance with [1].

2. Problem definition and experimental plan
The equation for calculating the hardness numbers on Rockwell scales contains the indenter penetration depth, but it is not the only quantity influencing Rockwell hardness numbers. Besides the indenter movement measurement uncertainty, the hardness measurement uncertainty on Rockwell and Superficial Rockwell scales is influenced by the measurement uncertainties of the following parameters: the applied force, the angle between indenter generatrix and the curvature radius (for Rockwell and Superficial Rockwell scales where cone indenters are used), the ball indenter diameter (for Rockwell and Superficial Rockwell scales where ball indenters are used), measurement cycle parameters. The expanded hardness measurement uncertainty is determined by equation (1):

\[ U = 2 \sqrt{\sum (C_i u_i)^2} \]  

where \( C_i \) – sensitivity coefficients, \( u_i \) – measurement uncertainty of the values influencing the hardness numbers on Rockwell and Superficial Rockwell scales. Sensitivity coefficients should be known for the calculation of the expanded measurement uncertainty. The sensitivity coefficient

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associated with the indenter movement measurement is equal to 0.5 HR/µm for Rockwell scales and 1 HR/µm for Superficial Rockwell scales. Other coefficients should be determined experimentally. The conducted experiments consisted in changing only one of the factors influencing the hardness measurement result by a known quantity and consequently in determining the change in the hardness value. Sensitivity coefficients are equal to the ratio between the hardness change and the change in the influencing quantities. The preliminary load changed by 0.239 N, while the main load changed by 0.597 N. The preliminary load application time changed by 1 s, the preliminary load exposure time changed by 2 s, the main load application time changed by 4 s for Rockwell scales and by 2 s for Superficial Rockwell scales. The main load exposure time changed by 4 s, and the final reading time changed by 4 s. The indenter velocity at which the maximum load is reached changed by 10 µm/s. When there was a change in the indenter speed, the main load application time changed as well, but this change was less than by 4 s, that is why it was not taken into account. Cone indenters with almost identical angles between generatrix were used to determine sensitivity coefficients of indenter geometrical parameters, the difference in the nose radii was equal to 2.3 µm. Cone indenters with approximately equal nose radii and a 0.1° difference in the angles between generatrix were used as well. Sensitivity coefficients for ball indenters were determined using two indenters with a 0.1 µm difference in diameters (for 1/16 inch ball). Hardness measurements were carried out on the test blocks made of steel and soft metals.

3. Experimental results
Table 1 shows sensitivity coefficients for preliminary loads, main loads, indenter geometrical parameters for different scales and hardness ranges.

### Table 1. Sensitivity coefficients for preliminary loads, main loads and indenter geometrical parameters.

| Scales | Ranges  | Sensitivity coefficients for preliminary loads, HR/N | Sensitivity coefficients for main loads, HR/N | Sensitivity coefficients for cone indenter angles, HR/° | Sensitivity coefficients for curvature radii of cone indenters, HR/µm | Sensitivity coefficients for diameter of ball indenters, HR/mm |
|--------|---------|-----------------------------------------------------|---------------------------------------------|-----------------------------------------------------|------------------------------------------------------------------|-----------------------------------------------------------------|
|        | 83 ± 3  | 0.084                                               | -0.134                                      | 0.4                                                 | 0.065                                                            | -                                                               |
| HRA    | 76 ± 4  | 0.460                                               | -0.218                                      | 0.7                                                 | 0.043                                                            | -                                                               |
|        | 65 ± 5  | 0.669                                               | -0.235                                      | 1.3                                                 | 0.013                                                            | -                                                               |
| HRB    | 90 ± 10 | 0.042                                               | -0.101                                      | -                                                   | -                                                                | 0.3                                                             |
|        | 60 ± 10 | 1.004                                               | -0.117                                      | -                                                   | -                                                                | 1.4                                                             |
| HRC    | 65 ± 5  | 0.251                                               | -0.067                                      | 0.4                                                 | 0.052                                                            | -                                                               |
|        | 45 ± 5  | 0.335                                               | -0.084                                      | 0.8                                                 | 0.03                                                             | -                                                               |
|        | 25 ± 5  | 0.418                                               | -0.101                                      | 1.4                                                 | 0.013                                                            | -                                                               |
| HR15N  | 92 ± 2  | 0.042                                               | -0.218                                      | 0.2                                                 | 0.078                                                            | -                                                               |
|        | 82 ± 2  | 0.084                                               | -0.302                                      | 0.3                                                 | 0.048                                                            | -                                                               |
|        | 72 ± 2  | 2.218                                               | -0.519                                      | 0.9                                                 | 0.035                                                            | -                                                               |
| HR30N  | 80 ± 4  | 0.084                                               | -0.285                                      | 0.3                                                 | 0.065                                                            | -                                                               |
|        | 65 ± 5  | 0.126                                               | -0.352                                      | 0.6                                                 | 0.039                                                            | -                                                               |
|        | 45 ± 5  | 1.715                                               | -0.503                                      | 1.1                                                 | 0.03                                                             | -                                                               |
| HR45N  | 75 ± 5  | 0.084                                               | -0.134                                      | 0.3                                                 | 0.052                                                            | -                                                               |
|        | 50 ± 6  | 0.879                                               | -0.318                                      | 0.7                                                 | 0.026                                                            | -                                                               |
|        | 25 ± 5  | 1.967                                               | -0.369                                      | 1.2                                                 | 0.022                                                            | -                                                               |
The experimental results demonstrate tendencies similar to [2, 3]. Standard type A uncertainties of sensitivity coefficient measurements do not exceed 5% of the sensitivity coefficients values.

| Scales | Ranges | Sensitivity coefficients for indenter penetratio speed, 10^{-6} s/\mu m | Sensitivity coefficients for preliminary load application time, HR/s | Sensitivity coefficients for preliminary load exposure time, HR/s | Sensitivity coefficients for main load application time, HR/s | Sensitivity coefficients for main load exposure time, HR/s | Sensitivity coefficient for final reading time, HR/s |
|--------|--------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| HR15T  | 92 ± 2 | 0.126                                           | -0.251                                          | -                                               | -                                               | 0.3                                             |
|        | 74 ± 2 | 1.172                                           | -0.553                                          | -                                               | -                                               | 0.6                                             |
| HR30T  | 81 ± 6 | 1.674                                           | -0.168                                          | -                                               | -                                               | 0.2                                             |
|        | 50 ± 6 | 1.883                                           | -0.519                                          | -                                               | -                                               | 0.8                                             |
| HR45T  | 75 ± 5 | 0.251                                           | -0.235                                          | -                                               | -                                               | 0.3                                             |
|        | 45 ± 5 | 1.548                                           | -0.284                                          | -                                               | -                                               | 0.9                                             |

Table 2 shows sensitivity coefficients for measurement cycle parameters for different scales and hardness ranges.

Table 2. Sensitivity coefficients for measurement cycle parameters.
The hardness measurement uncertainty budget on Rockwell and Superficial Rockwell scales was calculated according to equation (1). Table 3 shows expanded uncertainties of the national primary standard machine on Rockwell and Superficial Rockwell scales before and after improvement.

Table 3. Expanded uncertainties of hardness measurements on Rockwell and Superficial Rockwell scales carried by the national primary standard machine before and after improvement.

| Rockwell and Rockwell scales | Expanded uncertainty before primary standard machine, HR | Expanded uncertainty after primary standard machine improvement, HR |
|-----------------------------|--------------------------------------------------------|------------------------------------------------------------|
| HRA                         | 0.3                                                    | 0.2                                                       |
| HRB                         | 0.4                                                    | 0.2                                                       |
| HRC                         | 0.3                                                    | 0.2                                                       |
| HR15N, HR30N, HR45N         | 0.5                                                    | 0.3                                                       |
| HR15T, HR30T, HR45T         | 0.6                                                    | 0.3                                                       |

For example Table 4 shows comparison components of expanded uncertainty of HRA scale for old and new primary standard machine.

Table 4. Components of expanded uncertainty of hardness measurements on HRA scale carried by the national primary standard machine before and after improvement.

| Components of expanded uncertainty of hardness measurements on HRA scale | Value of component of expanded uncertainty before primary standard machine improvement, HR | Value of component of expanded uncertainty after primary standard machine improvement, HR |
|------------------------------------------------------------------------|------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| preliminary force                                                     | 0.11                                                                                     | 0.07                                                                                     |
| main force                                                            | 0.21                                                                                     | 0.14                                                                                     |
| displacement of indenter                                               | 0.06                                                                                     | 0.04                                                                                     |
| angle of indenter                                                     | 0.14                                                                                     | 0.09                                                                                     |
| curvature radii of indenter                                           | 0.05                                                                                     | 0.03                                                                                     |
| velocity of indenter                                                  | 0.05                                                                                     | 0.03                                                                                     |
| preliminary force application time                                    | 0.01                                                                                     | 0.01                                                                                     |
| preliminary force exposure time                                        | 0.08                                                                                     | 0.006                                                                                    |
| main force application time                                           | 0.005                                                                                    | 0.004                                                                                    |
| main force exposure time                                               | 0.015                                                                                    | 0.012                                                                                    |
| final reading time                                                     | 0.008                                                                                    | 0.006                                                                                    |

4. Conclusion
The national primary standard machine on Rockwell and Superficial Rockwell scales has been improved. The application of an indenter with geometrical parameters that are close to theoretical parameters for Rockwell cone indenter proved to be an important factor of uncertainty reduction. The application of a precision loading system along with a high-accuracy laser interferometer has made it possible to significantly reduce the hardness measurement expanded uncertainty on Rockwell scales.

5. References
[1] ISO 6508-1:2016 Metallic materials — Rockwell hardness test — Part 1: Test method
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[3] S.R. Low, “NIST Recommended Practice Guide: Special Publication 960-5: Rockwell Hardness Measurement of Metallic Material”, January 2001.