Society of Production Engineering

ICPES 2025

40. INTERNATIONAL CONFERENCE ON PRODUCTION ENGINEERING - SERBIA 2025

DOI: 10.46793/ICPES25.183P

University of Nis Faculty of Mechanical Engineering

Nis, Serbia, 18 – 19th September 2025

ASSESSMENT OF MEASUREMENT UNCERTAINTY IN MECHANICAL MATERIAL TESTING – THEORETICAL FRAMEWORK AND PRACTICAL APPLICATION

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Abstract: *This professional paper addresses a fundamental aspect of metrological quality assurance in mechanical material testing: the assessment of measurement uncertainty. Starting from the importance of reliable measurement results for industry, research, and development, the paper thoroughly elaborates on the theoretical framework of measurement uncertainty in accordance with international standards, primarily the GUM (Guide to the Expression of Uncertainty in Measurement) document. Special emphasis is placed on the clear distinction between measurement error and measurement uncertainty, as well as on different evaluation methods (Type A and Type B). General sources of uncertainty characteristic of mechanical testing are discussed, including the influence of equipment, the material/specimen itself, environmental conditions, and human factors.*

The methodology for assessing measurement uncertainty is presented step-by-step, from defining the measurement model and identifying input quantities, through calculating standard and combined uncertainty, to determining expanded uncertainty. The practical application of this methodology is demonstrated through a specific example of hardness determination by Rockwell method. For this example, key sources of uncertainty are analysed, and guidelines for their quantification are provided.

Keywords: *Mechanical material testing, Measurement uncertainty, Hardness determination, Product quality.*

1. INTRODUCTION

Measurement uncertainty represents a quantitative estimate of the quality of a measurement result. Unlike measurement error, which denotes the difference between the measured and the “true” value (usually unknowable in practice), uncertainty expresses the level of confidence that the measured result is close to the actual value. In other words, uncertainty does not claim to correct the result but rather describes the range within which the true value is reasonably expected to lie. This distinction between error and uncertainty is essential for proper interpretation of results, particularly in mechanical material testing, where results are often used for safety-critical decisions.

The international reference document for the assessment of measurement uncertainty is the Guide to the Expression of Uncertainty in Measurement (GUM), first published by ISO, IEC, and other organizations in 1993. The GUM establishes a systematic and harmonized methodology for evaluating and expressing uncertainty, making measurement results comparable across laboratories and countries. In addition to the GUM, specific standards are relevant for mechanical testing, such as ISO 6508 for Rockwell hardness testing or ISO 6892 for tensile testing, which provide both testing procedures and indications of relevant sources of uncertainty. Together, these standards ensure that both the test execution and the evaluation of its reliability follow internationally recognized best practices.

The GUM distinguishes two basic approaches to evaluating uncertainty: Type A, based on statistical analysis of repeated observations, and Type B, based on other sources of information such as instrument specifications, calibration certificates, or literature data. Type A evaluation allows the quantification of variability through repeatability and reproducibility studies, making it particularly useful in routine laboratory conditions. Type B evaluation, on the other hand, enables the incorporation of knowledge about systematic influences or limitations of the measurement system, even when repeated measurements are not available. In most practical cases, both approaches are combined, ensuring a comprehensive picture of the uncertainty budget.

Mechanical material testing is characterized by a wide range of potential uncertainty sources. Equipment-related sources include instrument calibration, resolution, and stability of applied forces or displacements. Material-related sources stem from the specimen itself, such as inhomogeneity, anisotropy, or preparation quality. Environmental factors, including temperature and humidity, may significantly influence results, particularly in sensitive tests. Finally, human factors, such as operator skill or the application of testing procedure, cannot be neglected, especially in semi-automated or manually controlled tests. Identifying and quantifying each of these contributions is the foundation of a systematic uncertainty analysis.

2. METHODOLOGY FOR ASSESSING MEASUREMENT UNCERTAINTY

The first step in assessing measurement uncertainty is to define the measurement model, i.e., the mathematical relationship that links the measurand (the quantity to be determined) with the input quantities that influence the result. For example, in Rockwell hardness testing, the model incorporates applied force, indenter geometry, depth measurement, and material response. According to the GUM, all sources of variability should be expressed as input quantities, each with an associated probability distribution. A well-defined measurement model ensures traceability and transparency, making subsequent calculations consistent and reproducible.

Once the measurement model is established, the next step is to identify all relevant input quantities and assign uncertainty values to each. Input uncertainties can originate from different sources: calibration data, instrument resolution, repeatability tests, environmental monitoring, or published literature. Depending on the available information, the uncertainty of each input quantity is evaluated either using the Type A method (statistical analysis of repeated measurements) or the Type B method (data from certificates, manufacturer specifications, expert judgment). Assigning an appropriate probability distribution (normal, rectangular, triangular, etc.) to each input is crucial for realistic propagation of uncertainty.

Each input uncertainty is expressed as a standard uncertainty, usually corresponding to a 1-sigma coverage (approximately 68% confidence level). The propagation of these uncertainties through the measurement model can be performed analytically (using sensitivity coefficients derived from partial derivatives) or numerically (e.g., Monte Carlo simulations). The result is the combined standard uncertainty, which represents the overall uncertainty of the measurand at the standard level of confidence. This step highlights how different sources contribute to the final result and prevents overlooking dominant factors.

For practical engineering and quality assurance purposes, uncertainty is usually expressed as an expanded uncertainty, which corresponds to a higher confidence level (typically 95%). This is achieved by multiplying the combined standard uncertainty by a coverage factor k, most commonly k = 2.

3. MEASUREMENT UNCERTAINTY OF MEASURED ROCKWELL HARDNESS – ASSESMENT EXAMPLE

Measurement uncertainty analysis is a useful tool to help determine sources of error and to understand differences in test results. Most product specifications have tolerances that have been developed over the past years based mainly on the requirements of the product but also, in part, on the performance of the machine used to make the hardness measurement. These tolerances therefore incorporate a contribution due to the uncertainty of the hardness measurement and it would be inappropriate to make any further allowance for this uncertainty by, for example, reducing the specified tolerance by the estimated uncertainty of the hardness measurement. In other words, where a product specification states that the hardness of an item shall be higher or lower than a certain value, this should be interpreted as simply specifying that the calculated hardness value(s) shall meet this requirement, unless specifically stated otherwise in the product standard. However, there might be special circumstances where reducing the tolerance by the measurement uncertainty is appropriate. This should only be done by agreement of the parties involved [SRPS 6508 2024].

The approach for determining uncertainty presented in this study considers only those uncertainties associated with the overall measurement performance of the hardness testing machine with respect to the hardness reference blocks (abbreviated as CRM). “CRM” stands for “certified reference material” (in hardness testing standards, certified reference material is referred to as a hardness reference block, i.e. a piece of material with a certified value and associated uncertainty). These performance uncertainties reflect the combined effect to all the separate uncertainties. Because of this approach, it is important that the individual machine components are operating within the tolerances. It is strongly recommended that this procedure is applied for a maximum of one year after the successful passing of a verification and calibration.

3.1 Procedure of calculation

The measurement uncertainty of the measured hardness values was derived according to the procedure defined in the standard SRPS EN ISO 6508-1:2024 based on the indirect calibration of the device, point 9 and Annex G [SRPS 6508]. This procedure calculates an expanded uncertainty U, associated with the measured hardness value. The approach to this calculation is given in Table 1 together with details of the symbols used. In this procedure, several uncorrelated standard uncertainty sources are combined by the Root-Sum Square (RSS) method and then multiplied by the coverage factor k = 2. The uncertainty contribution from a systematic source is then added arithmetically to this value.

Bias of the machine

The bias, b, of a hardness testing machine (also termed “error”) is derived from the difference between — the certified calibration value of the hardness reference block, and

— the mean hardness value of the five indentations made in the hardness reference block during calibration of the hardness testing machine and can be implemented in different ways into the determination of uncertainty.

Table 1. Calculation procedure

<table>
<tr><th colspan="2">Test method</th><th colspan="5">HRB</th><th colspan="5">HRC</th></tr>
<tr><td colspan="2">Hardness of CRM HCRM</td><td colspan="5">83,1</td><td colspan="5">55,6</td></tr>
<tr><td colspan="2">Machine display resolution δms</td><td colspan="5">0,5</td><td colspan="5">0,5</td></tr>
<tr><td rowspan="3">Data from Calibration certificate*</td><td>X CRM</td><td colspan="5">96.66</td><td colspan="5">45.42</td></tr>
<tr><td>b</td><td colspan="5">1.76</td><td colspan="5">0.92</td></tr>
<tr><td>U*HTM</td><td colspan="5">0.56</td><td colspan="5">0.48</td></tr>
<tr><td colspan="2">Measured uncertainty (from Calibration certificate) of machine
UHTM = U*HTM /2</td><td colspan="5">0.28</td><td colspan="5">0.24</td></tr>
<tr><td colspan="2" rowspan="2">Measured values</td><td>H1</td><td>H2</td><td>H3</td><td>H4</td><td>H5</td><td>H1</td><td>H2</td><td>H3</td><td>H4</td><td>H5</td></tr>
<tr><td>85</td><td>84</td><td>84.5</td><td>84.5</td><td>84</td><td>56.5</td><td>57</td><td>57</td><td>57</td><td>56.5</td></tr>
<tr><td colspan="2">$\overline{H} = \frac{H1 + H2 + H3 + H4 + H5}{5}$</td><td colspan="5">84.4</td><td colspan="5">56.8</td></tr>
<tr><td colspan="2">$S_H = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(H_i - \overline{H})^2}$</td><td colspan="5">0.42</td><td colspan="5">0.27</td></tr>
<tr><td colspan="2" rowspan="2">Bias $\boldsymbol{b} = \overline{H} - H_{CRM}$</td><td colspan="5">1.3</td><td colspan="5">1.2</td></tr>
<tr><td colspan="5">(10-45] ± 4 HRB
(45-80] ± 3 HRB
(80-100] ± 2 HRB</td><td colspan="5">± 1,5 HRC</td></tr>
<tr><td colspan="2">Bias b acceptable?</td><td colspan="5">Yes (1.3 < 2)</td><td colspan="5">Yes (1.2 < 1.5)</td></tr>
<tr><td colspan="2" rowspan="4">Rrepeatability range
$r = Hn - H1$
(Whichever is greater)</td><td colspan="5">H2-H1=-1</td><td colspan="5">H2-H1=0.5</td></tr>
<tr><td colspan="5">H3-H1=-0.5</td><td colspan="5">H3-H1=0.5</td></tr>
<tr><td colspan="5">H4-H1=-0.5</td><td colspan="5">H4-H1=0.5</td></tr>
<tr><td colspan="5">H5-H1=-1</td><td colspan="5">H5-H1=0</td></tr>
<tr><td colspan="2" rowspan="2">Maximum permissible repeat ability range, r, of the testing machine
(Whichever is greater)</td><td colspan="5">$\leq \mathbf{0,04(130} - \overline{H}) = 1{,}824$</td><td colspan="5">$\leq \mathbf{0,02(100} - \overline{\mathrm{H}})$=0,884
≤0,89</td></tr>
<tr><td colspan="5">-</td><td colspan="5">0,8 HRC</td></tr>
<tr><td colspan="2">r acceptable?</td><td colspan="5">Yes (1 < 1.824)</td><td colspan="5">Yes (0.5 < 0.89)</td></tr>
<tr><td colspan="2">$\boldsymbol{U_H = 1{,}14 * S_H}$</td><td colspan="5">0.48</td><td colspan="5">0,31</td></tr>
<tr><td colspan="2">$\boldsymbol{U_{ms} = \delta_{ms}/sqrt(2*3)}$</td><td colspan="5">0.20</td><td colspan="5">0.20</td></tr>
<tr><td colspan="2">Determination of the corrected expanded uncertainty
$\boldsymbol{U} = \mathbf{2}\sqrt{\boldsymbol{U_H^2 + U_{ms}^2 + U_{HTM}^2}}$</td><td colspan="5">1.2</td><td colspan="5">0.9</td></tr>
<tr><td colspan="2">Measurement result with modified hardness
$\boldsymbol{H} = (\overline{H} - b) \pm U$</td><td colspan="5">(84.4 - 1.3) ± 1.2
83.1 ± 1.2</td><td colspan="5">(55.8 - 1.2) ± 0.9
54.6 ± 0.9</td></tr>
<tr><td colspan="2">Measurement result with modified uncertainty
$\boldsymbol{H_U} = \overline{H} \pm (U + |b|)$</td><td colspan="5">84.4 ± (1.2 +1.3)
84.4 ± 2.5</td><td colspan="5">55.8 ± (0.9 + 1.2)
55.8 ± 2.1</td></tr>
</table>

4. CONCLUSION

The determination of measurement uncertainty in Rockwell hardness testing is a critical aspect of ensuring the reliability and traceability of hardness results in material testing. This paper has presented the theoretical framework of measurement uncertainty, emphasizing its role in quantifying the confidence level of test outcomes. Through a detailed description of the procedure for evaluating uncertainty in Rockwell hardness measurements, it has been demonstrated that a systematic approach, incorporating all relevant sources of variability, can significantly enhance the credibility of the testing process. By applying established metrological principles and uncertainty estimation methods, laboratories can ensure compliance with international standards and improve decision-making based on hardness values. Ultimately, understanding and managing measurement uncertainty is essential for maintaining quality control and supporting the integrity of mechanical property evaluations in industrial applications.

The results and methodology presented in this study provide a practical framework for laboratories and quality control departments aiming to improve the reliability of Rockwell hardness testing. By identifying and quantifying individual sources of uncertainty—such as instrument precision, operator variability, and environmental conditions, this approach enables targeted improvements in the measurement process.

ACKNOWLEDGEMENT

This research was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract No. 451-03-137/2025-03/200109).

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