# Measurement uncertainty explained based on Leeb Hardness tests

## Article Highlights (10 min read)

- Measurement uncertainty analysis is applied to understand differences in test results and to determine the source of error.
- The uncertainty of a Leeb hardness measurement system consists of a statistical component, a component inherent to the measurement device and a component arising from the metrological chain between national standards and the user device (traceability).
- Uncertainty is not a statistical analysis, accuracy, specification and tolerances, errors and mistakes done by the operators.
- Good practice to decrease the uncertainty.
- The best practice is to use the best equipment with the best calibrations such as ISO/IEC17025 and reduce the impact of specimen inhomogeneity by conducting between 3-10 measurements to compute the average, remembering that standard deviation plays an important role in uncertainty computation

# Why is hardness testing measurement uncertainty of great importance?

“In every measurement, even the most carefully performed, there is always a margin of doubt." That means that one can never be 100% sure that the measured value is the true value. To measure that "doubt" and to quantify it we use uncertainty. In everyday language, we used to express it as "give or take" e.g. the steel bar is 2 meters long give or take 1 cm, meaning that the bar has 2 meters ± 1 cm, hence 1.99-2.01. One needs to keep in mind that the measuring tape used to measure the steel bar was produced and calibrated according to another measuring tape or device and each of them had its own uncertainties.

For hardness testing devices, it is the combined uncertainty that is the greatest importance, because it accounts for that "doubt" across the entire device calibration process until the end product - a probe - is calibrated and confirmed to comply with specific standard. The probes are calibrated and checked against test blocks which were measured and calibrated with other testing devices which also had its uncertainty (doubt), because as indicated above, you can not be 100% sure that the value is what the device shows for each measurement. That's why the combined uncertainty is critical to know.

The measurement uncertainty is relevant for everyone who wishes to make good quality measurements and understand the results, to determine a "pass or fail" examination, or even when assessing the tolerance, where it is needed to know the uncertainty before deciding whether the required tolerances were met.

# If 100% confidence is impossible then what is sufficient?

Contrary to that "doubt" is the certainty also named confidence that we want to know when providing a measurement value. In metrology, typically we want to be 95% confident when providing the values. Interested readers are suggested to read about the coverage factor K in external internet sources (typically is set at 2 and indicates confidence of 95%, while K=1 indicates 68% confidence).

For example: We might say that the hardness value of a test block measures 780 HLD ± 6 HLD, where ± 6 HLD is the uncertainty. With k = 2, the statement implies we are 95% confident that the test block hardness is between 774 HLD and 786 HLD.

## How is it defined in ISO 16859 and what are its components?

Let us discuss one of the methods described in DIN EN ISO 16859-1, denoted as M2. Not math savvy readers can also skip this chapter and move to the next one. The uncertainty of a Leeb hardness measurement system consists of a statistical component, a component inherent to the measurement device and a component arising from the metrological chain between the national standard and the user device (traceability) and test block.

$$U = k\sqrt{U_H^2 + u_{ms}^2\left(\frac{U_{MPE}}{\sqrt{3}}\right)^2}$$

**Where:**

**U** - The combined expanded measurement uncertainty

**k** - Coverage factor (k=1, k=2)

**$u_H$** - Standard uncertainty of hardness testing machine (k = 1 or k = 2), your device for measurement on "Certified Reference Material (CRM)" - *id est.* a test block

**$u_{ms}$** - Standard uncertainty due to resolution of the hardness tester, e.g. 1 HLD.

**$u_{MPE}$** - Expanded uncertainty derived from the maximum permissible error

$$U_H = t \cdot S_H$$

**Where:**

**t** - Student's factor computed on the basis of the statistics tables (for 10 measurements the t=1.06 the lower number of measurements, the higher the t factor)

**$S_H$** - Standard deviation for measurements on CRM

$$S_H = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(H_i - H_{AVG})^2}$$

**n** - Number of measurements

**$S_{AVG}$**- Mean value of the measurement on CRM (test block)

$$U_{MPE} = E_{rel} \cdot H_{CRM}$$

And the last component of the Equoation, the uMPE.

**Erel** - Maximum permissible error given in ISO16859

**$H_{CRM}$** - value of the CRM (test block)

| Type of impact device | Leeb hardness of reference test block | Maximum permissible error (Erel) % |
|---|---|---|
| D, D+15 | <500 | ±4.0 |
| DL, S | <700 | |
| C, E | <600 | |
| G | <450 | |
| D, D+15 | 500 to 700 | ±3.0 |
| DL, S | 700 to 850 | |
| C, E | 600 to 750 | |
| G | 450 to 600 | |
| D, D+15 | >700 | ±2.0 |
| DL, S | >850 | |
| C, E | >750 | |
| G | >600 | |

# What impacts the uncertainty in simple words?

The calculation of uncertainty for the hardness testing measurements is a tedious process. Luckily there are some practical steps one can apply to combat the "measurement doubt" (read below). While various standards for different methods do compute the uncertainty in slightly different way, the principle behind remains the same for all testing methods. In simple words, the main factors influencing the uncertainty are:

- Accuracy and repeatability of the equipment
- Standard compliance parameters
- Hardness homogeneity of the test block used during the calibration and verification
- Testing procedures of the test piece

In this article, we skip the exact differential method for the simplicity, however an outcome of that computation would show that $u_H$ has the largest impact on the uncertainty, that is number of measurements taken (impact on t-students factor) and standard deviation, driven not only by the number of measurements, but also repeatability (also defined as precision) of the measurement device.

# What is the best practice?

The combined uncertainty has three components; uncertainty of the probe, uncertainty due to inhomogeneity of the test piece, and the max uncertainty due to the standard compliance (in this example this is DIN EN ISO 16859). The user has an impact on all three components by:

1. Ensuring the best quality of devices and their calibrations
2. Conducting a sufficiently high number of measurements of the test piece
3. Choosing the probes that comply to the most rigorous standards.

**Step 1**

**To ensure the best quality of calibrations,** the users are recommended to calibrate their devices to accredited calibrations such as ISO/IEC 17025 and with best tools available, where each of the calibration components that play even a minor role is checked validated and approved by external independent auditors.

An important component of the calibration process is the hardness homogeneity of the test block. A CRM with uniform hardness across its entire surface ensures that each indentation made during the calibration process yields consistent results. This consistency reduces the variation in the calibration data, leading to lower standard deviation and, consequently, lower uncertainty in the calibration. Poor homogeneity increases the uncertainty component related to the reference block, which then propagates through the entire uncertainty budget of the hardness tester.

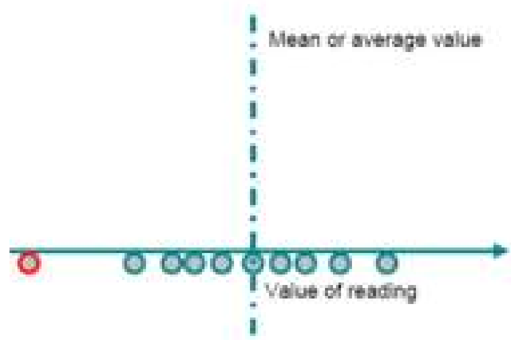
**Step 2**

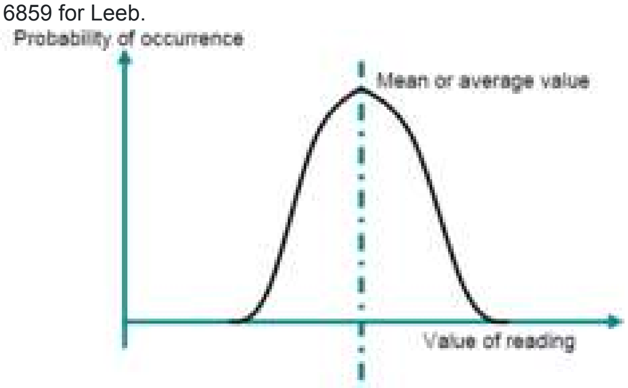
**To minimize the impact of test piece inhomogeneity the users are suggested to increase the number of measurements.** How many readings should you take?
When more individual readings are used to obtain the final result, we will be more certain that the calculated average is closer to the actual hardness of the test piece. However, performing more measurements could take extra effort and yields with marginal overall improvement in the data. As a rule of thumb, anything between 3 and 10 readings is generally acceptable unless stated otherwise.

- Taking 10 readings is a common choice as this reduces the statistical uncertainty, averages outliers and makes the arithmetic easy.
- In some cases taking 3 readings is sufficient. This practice is common where test pieces are comparatively homogeneous in hardness, and when the surface of the test piece is well prepared. For example some cast iron types with biphasic microstructures will have higher uncertainty by default, due to possible data spread.
- Taking 20 or even 50 readings only gives a slightly better estimate than 10.

**Step 3**

**To ensure the best standard compliance,** choose a device that complies with the most rigorous standards: DIN50159 Chinese GB/T 34205 for UCI and international DIN EN ISO 16859 for Leeb.




# What is not an uncertainty?

Having invented the Leeb method over 48 years ago, we came across various definitions of uncertainty and understanding of users, that are clearly not uncertainties at all. Below is the short list of what is **NOT** an uncertainty:

- **Statistical analysis** is not the same as uncertainty analysis. Statistics are usually used in uncertainty calculations but can be used to draw conclusions which go beyond the usage for uncertainty calculations.
- **Accuracy** (or rather inaccuracy) is not the same as uncertainty. Correctly speaking, ‘accuracy’ is a qualitative term (e.g. you could say that measurement was ‘accurate’ or ‘not accurate’). Uncertainty is quantitative. A ‘plus or minus figure’ may be called uncertainty, but not accuracy.
- **Specifications and tolerances** are not uncertainties. While specifications state what can be expected from a product (incl. ‘non-technical’ qualities such as its color), tolerances could be referred to as acceptance limits which are chosen for a process or a system.
- **Errors** are not the same as uncertainties, especially in the past it’s been common to use the words interchangeably. An error usually refers to a malfunction within the system. However, recently also the term ‘error’ has been used synonymously with ‘bias’, which usually is considered as a component of the measurement uncertainty.
- **Mistakes made by operators** are not measurement uncertainties. They should be avoided by working carefully and by double-checking work.

# References

Metallic materials — Leeb hardness test — Part 1: Test method, DIN EN ISO16859-1

Metallic materials — Leeb hardness test — Part 2: Verification and calibration of the testing devices, DIN EN ISO16859-2

Portable Hardness Testing. Theory Practice, Applications, Guidelines. Burnat, D., Raj, L., Frank, S., Ott, T. Schwerzenbach, Screening Eagle Technologies AG, 2022.