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1. Relevance of ASTM Standards for Leeb Metal Hardness Testing

Conformance of Equotip hardness testers with the various ASTM hardness testing standards are of particular concern to users e.g. with applications in the petrochemical industry who refer to API. This document will outline the current situation within standards.

ASTM A956 (Leeb)

The Equotip Leeb series of hardness testers are standardized in ASTM according to A956-06 “Standard Test Method for Leeb Hardness Testing of Steel Products”. This standard was originally approved and published in 1996, and the next to last edition was published in 2012. This is the only ASTM standard that currently addresses testing with the Leeb method.

The Leeb method measures the ratio of rebound velocity to impact velocity of a defined impact body launched against a surface at a defined velocity. Therefore the Leeb method measures the loss of kinetic energy during impact, and is thus considered a dynamic technique. The accuracy of a Leeb test is dependent on proper test conditions – surface roughness, test piece thickness, and mass – which are defined in the A956 standard.

The A956 standard is not known to be specifically referenced by any current API standard. However, the Equotip conveniently converts hardness measurement values and displays the results in other hardness scales, such as Brinell, Rockwell, and Vickers. The ASTM standards governing these test methods are generally mentioned in API standards.

ASTM E140 (Hardness Conversions)

This standard covers hardness conversions for metals and the relationship among Brinell hardness, Vickers hardness, Rockwell hardness, Superficial hardness, Knoop hardness, Scleroscope hardness and Leeb hardness.

ASTM E10 (Brinell)

This standard covers the Brinell test method as used by stationary, typically bench-top machines. This standard does not apply to portable devices like the King Brinell (hydraulic force application) or comparative testers like the Telebrineller, as these devices do not conform to the force application requirements of the test method.

ASTM E18 (Rockwell)

This standard covers the Rockwell test method as used by stationary, typically bench-top machines. It does not apply to portable devices, as these devices do not conform to the force application requirements of the test method.
ASTM E110 (Portable Testers)
This standard covers portable Brinell and Rockwell testing devices. These devices typically use the same indenter (diamond cone, tungsten carbide ball) as defined in the E10 and E18 standards. However, the devices are designed for portable use and generally do not conform to E10 and E18 for the reasons stated above. E110 is currently involved in a revision ballot to modify the structure and requirements to be as similar as possible to the E10 and E18 standards.

ASTM A833 (Comparative Brinell – Telebrineller)
This standard covers the method that compares an indentation on a reference bar to the indentation on the test surface. The ratio of the indentations provides a measure of hardness. This method is generally considered to be less accurate than those of E110 and E10.

ASTM A1038 (UCI – Ultrasonic Contact Impedance)
This standard covers the method named Ultrasonic Contact Impedance (UCI), which uses a calibrated rod with a diamond indenter (typically a Vickers indenter) attached to one end. The rod is vibrated ultrasonically to a resonance frequency and pressed into the test surface with a pre-defined force (usually Vickers forces). The instrument measures the shift in harmonic frequency which varies according to the depth of penetration. This frequency shift is converted and displayed directly into a common hardness scale like Rockwell, Brinell or Vickers.

This method is strongly affected by a change in material, and therefore must be calibrated specifically to a sample of the material to be tested. It cannot use the concept of material groups like the Leeb method, as the relationship between the frequency shift and the common hardness scales is immensely material-dependent.

ISO 16859 (to be published in 2015)
This standard covers the determination of the Leeb hardness of metallic materials using six different Leeb scales (HLD, HLS, HLE, HLDL, HLD+15, HLC, HLG).

DIN 50156 (Leeb)
This German standard is a national standard that includes traceable calibrations of test blocks and instruments to a national Leeb etalon. These calibrations are done by ISO 17025 accredited organizations in Germany whose Leeb calibration instruments are traceable to the German national laboratory (named PTB). Also UKAS calibration of Leeb reference test blocks is now available.

DIN 50159 (UCI) Conclusions
This particular national German standard covers the Hardness testing of metallic material with the UCI test method as well as verification and calibration of the testing devices. If conversions to other hardness scales are used, testing on reference samples is strongly recommended to verify the accuracy of the conversion. These reference measurements can then be used to reach intercompany / interlaboratory agreement on the testing procedures and inspection records.
2. Measurement Uncertainty for Leeb Hardness Tests

In every measurement even the most carefully performed, there is always a margin of doubt. Measurement uncertainty analysis is applied to understand differences in test results and to determine sources 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 standard and the user device (traceability).

Symbols

Applying the denominations from DIN 50156, commonly used symbols in Leeb hardness uncertainty are as follows:

- $u_{HTM}$: uncertainty of hardness testing machine ($k = 1$ / $k = 2$)
- $n$: number of measurements
- $u_x$: uncertainty due to in-homogeneity of test piece
- $k$: coverage factor
- $u_E$: uncertainty due to maximum permissible error
- $s_x$: standard deviation
- $u_{ms}$: standard uncertainty due to resolution of measuring system
- $t$: Student's factor
- $U_C$: combined measurement uncertainty ($k = 2$)

Applicable Standards

The reader shall refer to DIN 50156-1 and ISO/FDIS 16859-1 for detailed instructions to calculate Leeb measurement uncertainties.

Expressing Uncertainties of Measurement

We might say that the hardness value of a test block measures $780 \text{ HLD} \pm 6 \text{ HLD}$, where $\pm 6 \text{ HLD}$ is the uncertainty. With $k = 2$, the statement implies we are 95% certain that the test block hardness is between 774 HLD and 786 HLD.

Combined Uncertainty

The uncertainty of an Equotip hardness tester and the hardness test block can be found on the calibration certificates of the Leeb impact device and of the test block, respectively.

The standard DIN 50156-1, e.g., provides two methods M1 and M2 to calculate the uncertainty for a hardness measurement conducted by the user on a test piece.

Here is an example of measurement using method M2:

1. The calibration certificate of an Equotip Leeb impact device D may read $U_{HTM} (k = 2) = 5.8 \text{ HLD}$ for the expanded uncertainty, with a combined uncertainty value of $u_{HTM} (k = 1) = 2.9 \text{ HLD}$.

2. A series of 10 readings taken on a test piece (e.g. steel roll, motor block) are assumed to average as $780.2 \text{ HLD}$ with a standard deviation of $s_X = 2.2 \text{ HLD}$, therefore the uncertainty will be as follow:

$$u_x = \frac{t \times s_X}{\sqrt{n}} = \frac{1.09 \times 2.2}{\sqrt{10}} = 0.076 \text{ HLD}$$
3. For a test on the sample of ~780 HLD, first the maximum permissible error of the bias is calculated where a factor of 1/2.8 is used to account for the case of the standard uncertainty of a rectangular distribution.

<table>
<thead>
<tr>
<th>Hardness of test block</th>
<th>Maximum permissible error of tester</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 450 HL</td>
<td>±4.0 %</td>
</tr>
<tr>
<td>450-750 HL</td>
<td>±3.0 %</td>
</tr>
<tr>
<td>≥750 HL</td>
<td>±2.0 %</td>
</tr>
</tbody>
</table>

To find the combined uncertainty of the measurement with a given Equotip Leeb impact device on a test piece, we need to calculate the geometric mean as follow:

\[
U_C(k=2) = \sqrt{U_{HTM}^2 + U_X^2 + U_E^2} = \sqrt{2.9 + 0.76 + 5.6} = 12.7 \text{ HLD}
\]

Based on this example, the average hardness of 780.2 HLD of the test piece measured with the given Equotip Leeb impact device would hold an uncertainty of 12.7 HLD.

“How many readings should I 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 on our 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 outlays 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.
- Using 20 or even 50 only give a slightly better estimate than 10.
**What Measurement Uncertainty is Not**

**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 a 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.
3. Influence of Elevated Temperatures on Leeb Hardness Testing

Scope
Temperature has a direct influence on the mechanical properties of metallic materials. Proceq Equotip Leeb testers are used for a wide variety of applications where the influence of temperature is unavoidable. Applications can include manufacturing environments where components are being tested as they come out of the heat treatment oven or on-site inspection in locations affected by desert heat. When dealing with elevated temperatures it is very difficult to eliminate the effect. There have been very few case studies highlighting the influence of temperature on hardness testing to date. This case study is the first to evaluate the effect of temperature on the Leeb hardness principle.

Test setup and procedure
Selected Leeb test blocks at three different HLD hardness levels were physically heated up to 200°C (392°F), and the hardness was measured as the temperature gradually decreased. The testing was carried out with impact device D on carbon steel test blocks. Note that other metals may show different results.

Test results and conclusions
Data obtained for each hardness level reveal clear influence of temperature on hardness of the different carbon steel blocks. The results display a linear dependence of the Leeb (HLD) value on temperature, independent of the hardness level.

Notably, when the HLD values are converted to other commonly used hardness scales such as HV, the non-linear temperature-dependent conversion relationship does not yield the same linear dependence.
4. Heavy Use Instructions

Equotip Leeb hardness testers are designed for portable applications in industrial environments. A few simple precautionary steps can improve the performance as well as prolonging the service life of your device.

Preparing the Tester

- Only use the Proceq supplied or specified mains adapters for charging the instruments battery. The device can also be operated directly from the mains adapter without batteries.
- Equotip cables are optimized to have additional flexibility. However it is highly recommended to avoid sharp bends in the cables and sudden loads on connectors (these can occur, for example, if the cables get caught or coiled).
- Using the test block supplied check your Hardness Tester on regular basis to make sure it is operating properly.

Preparing the Probe

Minimize dirt build-up on the impact device and ensure accuracy by:

- Removing dirt, oil, grease, and other contaminants from the measuring point
- Machining the surface as per chapter “Surface Roughness Requirements for Accurate Hardness Measurements”
- Removing metal dust and abrasive grit with a cloth.
- Placing the sample on a solid support base or in a holder / fixture.

Note: Use the surface roughness comparator plate provided in order to meet the required surface condition for the test method/principle.

Measurement Procedure

1. Hold the black loading tube with your pointer finger, middle finger, and ring finger on one side and your thumb on the other side. With the other hand, hold the coil casing as close as possible to the support ring.

2. Load the impact device in the air by slowly and evenly sliding the loading tube as far as it will go in the direction of the coil housing. Then slowly draw the loading tube back, never allowing it to snap back abruptly.

   Please note: Do not load the impact device directly on the test piece.

3. Slightly depress the release button with your thumb and wait for approximately

   Note: When performing measurements, wear clean gloves and take extra care not to touch the guide tube with dirty hands.
Routine Maintenance and Inspection

- Clean the guide tube at the end of each working day by inserting the Proceq brush, using rotating and rubbing motion.
- **Clean the support ring and the impact body** (especially indenter ball and catch pin) with acetone.
- Yearly inspection of the instrument by a Proceq-certified Service & Repair Centre is recommended.

Note: Every week, clean the impact device from the inside (using an acetone-soaked cotton swab) and outside (using an acetone-soaked cloth).

Proper Storage

- Never leave the impact device out on the workbench.
- Do not coil the cable tightly.
- **Clean the test surfaces of the hardness test block with acetone** and cover with Proceq protective sticker.
- Store in an Equotip case in a dry location at room temperature.
5. Durability Study for Equotip Leeb, Impact Devices

Objective

Proceq Equotip Leeb Impact Devices are Swiss Made and manufactured in a way as to ensure best-in-class quality. Equotip users value the long-term stability of the Leeb hardness scales that Proceq has provided over 40 years. To highlight this and as part of Proceq's production inspection, Proceq conducted a series of tests to quantify the durability of its impact devices.

Procedure

The durability tests were performed in an automated way on a customized CNC machine under well-defined and controlled conditions.

Each impact device was initially calibrated to the Proceq traceable reference. A reference test block was then measured according to DIN 50156-2 using 10 impacts spread across the surface of the test block. The average hardness value was calculated and checked against the given tolerance. The complete procedure was repeated with test blocks of different hardness levels, for various types of impact devices.

Results

The results are shown in the table and graphs below. For each test, the out of tolerance point was reached due to wear of the impact body, whereas the impact device itself still was in good condition.

Equotip Leeb G impact device is typically used on heavy-duty castings and forged parts and averages a hardness often around 35 HRC or 325 HB. Thus it is expected that the impact body will reach a lifetime of 100'000 impacts based upon a hardness of 35 HRC.

The very versatile Equotip D Leeb impact device is found to last longer than device G, which is mainly due to the smaller indenter sphere as well as the lower impact energy. To many users such a lifetime essentially means that the impact body never has to be replaced.

Once the hardness of the test piece approaches 60 HRC the impact body D wears out faster. This is where the impact device S is useful, showing exceptional durability even at 61 HRC. The Equotip Leeb S impact device is only outdone by the E impact device (results not shown), which uses a diamond indenter sphere and shows no wear after many impacts on very hard metals.

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Durability test carried out on hardness level</th>
<th>Number of impacts done before drift (+/- 4 HL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>550 HLG (~ 35 HRC)</td>
<td>100'000 *</td>
</tr>
<tr>
<td>D</td>
<td>600 HLD (~ 35 HRC)</td>
<td>&gt; 300'000</td>
</tr>
<tr>
<td>D</td>
<td>775 HLD (~ 56 HRC)</td>
<td>&gt; 300'000</td>
</tr>
<tr>
<td>D</td>
<td>820 HLD (~ 61 HRC)</td>
<td>3'000 *</td>
</tr>
<tr>
<td>S</td>
<td>830 HLS (~ 61 HRC)</td>
<td>&gt; 200'000*</td>
</tr>
</tbody>
</table>

For D device on 600 and 775 HLD impact device and body still worked reliably even after 300'000 impacts. With all the other tests, the impact body was the limiting factor.
Selected Wear and Tear Trend Curves

Overall, the tests re-confirm the well-recognized high performance standards of Equotip Leeb impact devices. Please note that results can vary depending on the surrounding environment (e.g. dirt, metal dust, handling, etc...) where the testing is taking place. A rough environment can have a negative effect on both the impact device and body.
6. Using Equotip Leeb Support Rings

Leeb hardness testers provide accurate measurements if the impact body has a certain position in the guiding tube at the moment of its impact onto the test surface. When testing flat samples with standard support rings, the spherical test tip is located precisely at the end of the guiding tube. However, when testing curved samples with the standard support rings, this may not always be the case. To ensure accurate measurements in all cases, Proceq offers a range of special support rings designed for measurements on curved sample surfaces.

Most common test situations: Equotip Leeb impact devices D/DC, C, E, S and G with standard support rings

With each Leeb impact device D/DC, C, E, S or G, respectively, Proceq delivers two support rings. The 13.5 mm outer diameter (OD) support ring – named “D6a” – provides accurate results if the test surface curvature is larger than \( R = 30 \) mm. The 19.5mm OD support ring D6 can be used down to a minimum test surface curvature of \( R = 60 \) mm. Equotip Leeb G impact devices come with two support rings with 19.5 mm (G6a) and 29.5 mm OD (G6), respectively. These provide accurate measurements as long as the surface curvature of the sample has a radius above 50 mm for G6 and 100 mm for G6a.

For test surfaces that do not comply with these standard situations, Proceq’s special support rings offer apt solutions for impact devices of types D/DC, C, E and S.
Testing on cylindrical test surfaces (e.g. boilers and pipes)

Cylindrical test objects can be tested with the support rings Z10–15 (R = 10 to 15 mm cylinder radius), Z14.5–30 (R = 14.5 to 30 mm), and Z25–50 (R = 25 to 50 mm cylinder radius). The support rings HZ11–13, HZ12.5–17, and HZ16.5–30 are well suited for Leeb hardness measurements on hollow-cylindrical surfaces, such as the inside of pipes and boilers of R = 11 to 13 mm, R = 12.5 to 17 mm, and R = 16.5 to 30 mm cylinder radii, respectively.

For convenience particularly when used with Proceq’s advanced Leeb impact devices, these support rings can be rotated by 360° around the longitudinal axis of the impact device. By means of a grub screw, the user can freely align the rectangular support ring to match the orientation of the impact device handle and to find the optimal position with respect to the sample.

Testing on spherical test surfaces

For spherical test situations, Proceq offers the support rings K10–15 (10 to 15 mm spherical radius) and K14.5–30 (R = 14.5 to 30 mm spherical radius). Accordingly, hollow-spherical surfaces can be tested with the support rings HK11–13 (R = 11 to 13 mm spherical radius), HK12.5–17 (R = 12.5 to 17 mm spherical radius), and HK16.5–30 (R = 16.5 to 30 mm spherical radius). The support rings for spherical test requirements are symmetrical around the guide tube, eliminating the need of alignment of the support ring.

Testing in recesses

For hardness tests inside recesses such as the bases between the teeth of gears, the support rings of the above-mentioned impact devices do not fit. For these situations, Proceq offers the DL long tip system. This is a special impact body and support ring combination, which can reach into many such recesses.

Universal support ring

The most versatile support ring is called UN. This ring embraces the need to test even more complex geometries. Examples can be seen below.

If none of these solutions apply to your sample geometry, please contact your local Proceq representative.
7. Combined Equotip Leeb and Portable Rockwell measuring methods

How to make hardness testing easy using the combined method of Equotip Leeb & Portable Rockwell C to increase repeatability and to produce reliable measurement data

Hardness testing is not always as straightforward when dealing with non-ideal samples, due to lack of mass, thickness and other critical geometries. Although there is no mathematical relationship between different test methods it is a common practice to correlate them to one another.

The existing default hardness conversions in Equotip Leeb devices are based on specific sample geometries. A Portable Rockwell probe has almost no restriction in regard to thickness and mass. For samples that don’t meet the Leeb specification a simple custom correlation based on the Portable Rockwell measurements enables the user to apply a correction factor and create a new hardness conversion. This can be achieved following four simple steps:

Note: Sample preparation is a critical factor and should be done prior to testing in order to avoid any undesirable discrepancy.

Step 1

Mark an area for testing on your sample and perform the test with Portable Rockwell. Choose what hardness scale you desire and note down the average value.

Note: It is recommended to perform 3-10 impacts/indentations and take the average (based on ISO 16859 and ASTM A956 standards).
Step 2
Perform the testing with your Equotip Leeb impact device on the same area and make a note of the Leeb value, i.e. HLDL. Now you should have **two sets of Equotip values**, static hardness measurement obtained by portable Rockwell probe and the dynamic hardness measurement from the Leeb probe.

Native Equotip HLDL and default HV conversion

Default portable Rockwell HV Conversion

Note: There is a significant difference between Portable Rockwell and HLDL default conversion values.

Step 3
In the Equotip 550 menu screen press the Wizards button, **Conversion Curve Creation → One point (offset of existing conversion)** and follow the on-screen instruction to create a new curve (please see the Equotip 550 operation instruction for more info).

Note: since this method is based on one point correlation, it is important to set the range as narrow as possible, covering only what is specified by the test procedure or the standard, highlighted in yellow.
Step 4
Choose the new material/curve you’ve just created from the main measuring screen. Now the hardness test results from Equotip HLDL should match the measurements in the desirable scale obtained by portable Rockwell probe and testing can be extended to heat affected zone and the weld with Equotip HLDL probe.
8. Surface Roughness Requirements for Accurate Hardness Measurements

How much surface preparation is required to achieve correct and reproducible hardness measurement values? Proceq evaluated measurements taken with Equotip impact devices under varying surface roughness conditions, to provide a guideline for obtaining the best results with respect to accuracy and reproducibility.

Sample Preparation

The surface of a Mn-Cr-V tool steel was prepared using grinding paper of grit sizes P40, P80, P120, P150, P180, and P240. After each grinding step, the surface roughness Ra was measured using a commercially available surface roughness tester. The hardness measurements were taken with Proceq’s Equotip Leeb impact devices types G, D, and C, as well as with Proceq’s Portable Rockwell Probe.

Results

The graphs 1 to 4 convey three important messages from the experiments:

• Amongst the Leeb hardness testers, measurements done with impact device G are least affected by rougher surfaces. This is due to the higher impact energy and larger ball indenter radius of impact device G (90 Nmm, 5 mm) compared to the D device (11 Nmm, 3mm) and C device (3 Nmm, 3mm), respectively. On rough surfaces, the indenter of the C device in particular, only impinges on surface irregularities giving a low hardness measurement which is not representative of the material. Also for the Portable Rockwell Probe, the susceptibility to erroneous hardness readings due to surface roughness is less significant than for Leeb D and C devices. The Portable Rockwell device determines the hardness according to the Rockwell principle while using a lower load of 50 N.

• The scatter of hardness readings taken with impact devices D and especially C increases quickly with rougher surfaces. It can be seen that this effect is much less in the data recorded for the G and the Portable Rockwell devices.

• For the given steel surface, impact device G yields reasonably reliable hardness values after surface preparation with a P80 grit grinding paper. In the case of Portable Rockwell and Leeb impact device type D, it is recommended to obtain, at least, a P120 grit surface finish. With impact device C it is possible to achieve higher precision results on smaller and thinner samples than with devices D and G, however, the greater demands on the surface finish are greater, (P180 grit).
Note: The presented degrees of surface preparation should be considered as a guideline only. Particularly in the case of softer metals, a finer grit sandpaper may be required. Use the surface roughness comparator plate provided in order to meet the required surface condition for the test method/principle.

Further Provisions

- In order to overcome the increased uncertainties of the results due to scatter on rough surfaces, the number of readings should be increased, along with the selection of the most suitable impact device.

- In case the readings deviate systematically from the actual sample hardness, the bias may be accounted for through a user-specific conversion (e.g. an offset). This is possible in most Equotip instruments. The individual bias correction needs to be worked out through measurements on two samples (one rough, one smooth) that have the same hardness.

Summary

Depending on the test application, different hardness tests and probes can be used. The selection of the right instrument shall be related, amongst other things, to the surface preparation. As a general rule for hardness tests: the better the surface condition, the more accurate and reproducible the measurement results. During surface preparation, however, it is critical not to alter the hardness through hot or cold working. In case surface conditioning has to be limited for economic reasons, utilities such as user-specific conversions or adaptations of the testing procedure should be considered.