

PAPER • OPEN ACCESS

## Mechanical properties measurements with portable hardness testers: advantages, limitations, prospects

To cite this article: K V Gogolinskii *et al* 2019 *J. Phys.: Conf. Ser.* **1384** 012012

View the [article online](#) for updates and enhancements.



**IOP | ebooks™**

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

# Mechanical properties measurements with portable hardness testers: advantages, limitations, prospects

K V Gogolinskii<sup>1</sup>, V A Syasko<sup>1</sup>, A S Umanskii<sup>1</sup>, A A Nikazov<sup>2</sup> and T I Bobkova<sup>3</sup>

<sup>1</sup> Saint-Petersburg Mining University, 2, 21st Line, St Petersburg 199106, Russia

<sup>2</sup> Constanta ltd, 21 lit. A, Ogorodniy per., St-Petersburg, 198097, Russia

<sup>3</sup>NRC "Kurchatov Institute" - CRISM "Prometey", 49 Shpalernaya str., St. Petersburg, 191015, Russia

E-mail: [nanoscan@yandex.ru](mailto:nanoscan@yandex.ru)

**Abstract.** The article presents an analysis of the most common hardness measurement methods, implemented by portable hardness testers: rebound or Leeb method, static Portable Rockwell (PR) method and Ultrasonic Contact Impedance (UCI) method. These methods are reviewed in terms of the physical nature of the measurements and the influence of the measured sample properties and the probe parameters on the measurement result. The review contains advantages of each method, possible applications, as well as limitations due to the operation principles of probes. The article also contains the analysis of solving the problem of measurement results validity and their conformity with standardized hardness scales.

## 1. Introduction

One of the most important mechanical properties, determining material condition, its strength and performance characteristics, is hardness. Hardness measurement is the most common way to control the mechanical properties of materials. Hardness is not a uniquely determined value, but is a complex parameter, associated with the primary mechanical characteristics of materials, depending on test methods [11]. The hardness values measured by static methods (Brinell, Rockwell, Vickers, Knoop) are functionally related to the value of the average contact pressure under the indenter  $p_d$ , determined by the ratio of the applied load  $P$  to the projected area  $A$  of contact of the indenter with test surface:

$$H \sim p_d = P/A [N/m^2].$$

The value of the contact pressure under the indenter in case of developed plastic strains for metals is determined by the ratio  $p_d = c\sigma_y$ , where  $\sigma_y$  is the yield strength,  $c$  – constraint factor [1]. Hence, for static hardness scales  $H \sim c\sigma_y$ . The value  $c$  depends on the material properties and shape of the indenter, and shall be approximately equal to 3 for metals.

The instruments, performing the measurement of the hardness values per static scales, in most cases are stationary laboratory testers. In case of inspection of large parts or equipment elements, it is required to cut special samples, resulting in integrity damage, which is often impossible or unacceptable. A separate task is quality control and inspection of welds and walls of pipelines, oil and gas storage facilities, high-pressure vessels and other metal structures at operating site. The solution of this problem is connected with the development of portable hardness testers. Measuring transducers (probes) of portable hardness testers are characterized by small size and low power consumption, enabling to perform measurements outside the testing laboratories directly at the tested items. When using portable hardness testers, it is necessary to take into account that the applied measurement



methods do not correspond to the standardized hardness scales, the values of which are usually specified in the technical documentation ( $HB$ ,  $HV$ , or  $HRx$ ), and the hardness values reproduced by them only to some extent correspond to these scales.

## 2. Leeb dynamic hardness testers

The principle of Leeb method [2] is measurement of the ratio of falling impact body velocity before and after collision with the surface of the test sample. Leeb hardness  $HL$  is calculated using the equation:

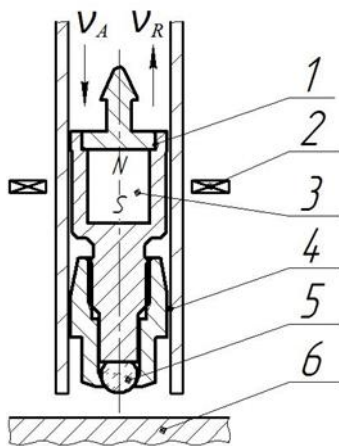
$$HL = (v_R/v_A) * 1000 ,$$

where  $v_R$  – impact body rebound velocity,  $v_A$  – impact velocity.

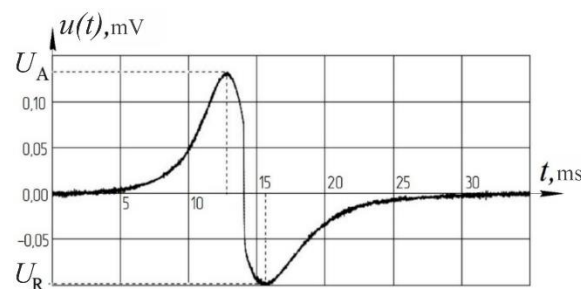
The implementation of Leeb method (Figure 1) is based on measurement of velocity of the impact body through the electromotive force (EMF) generated by the magnet installed inside the impact body, passing through the inductor coil mounted on the guide tube of the unit. The induced EMF is proportional to the magnet velocity. Induced EMF signal (Figure 2) is recorded, and the peak values of the induced voltage are used to calculate the Leeb hardness values using the equation:

$$HL = (U_R/U_A) * 1000 ,$$

where  $U_R$  and  $U_A$  – EMF amplitude, proportional to  $v_R$  and  $v_A$ , respectively.



**Figure 1.** Leeb hardness measurement scheme: 1 - impact body, 2 - inductor coil, 3 - permanent magnet, 4 - guide tube; 5 - indenter ball; 6 - test sample.



**Figure 2.** EMF diagram  $u(t)$ , induced in the coil during hardness measurement.

In the literature, the value of the ratio of impact body rebound velocity  $v_R$  to impact velocity  $v_A$  is called coefficient of restitution  $e$ . The theoretical analysis of the restitution coefficient dependence on the material properties and the impact body parameters is based on the solution based on the quasi-static approach to finding contact stresses in case of plastic impact, as described in [3]:

$$e^2 \equiv \frac{v_R^2}{v_A^2} = \frac{3\pi^{5/4}4^{3/4}}{10} \left( \frac{p_d}{E^*} \right) \left( \frac{1}{2} \frac{mv_A^2}{p_d R^3} \right)^{-1/4} ,$$

where  $m$  is impact body weight,  $R$  is indenter ball radius,  $p_d$  - average contact pressure under the indenter,  $E^*$  - the reduced plane strain modulus calculated from the ratio:

$$\frac{1}{E^*} = \frac{(1-\mu_m^2)}{E_m} + \frac{(1-\mu_b^2)}{E_b}, \quad (1)$$

where  $E_m, \mu_m$  and  $E_b, \mu_b$  are Young's moduli and Poisson ratios of tested material and the indenter ball, respectively. If we take the empirical relation between the yield strength of the tested material and the average contact pressure for metals:  $p_d \approx 3.0\sigma_d$  ( $\sigma_d$  - dynamic yield stress), then:

$$e \approx 3.8(\sigma_d/E^*)^{1/2} \left( \frac{1}{2} m v_A^2 / \sigma_d R^3 \right)^{-1/8}.$$

From this equation it follows that, in general, the restitution coefficient, and, consequently, measured Leeb hardness value, depend on the ratio of the yield strength  $\sigma_d$  and the modulus of elasticity  $E_m$  of tested material, as well as on the parameters of measuring probes of hardness testers (so-called "impact device"): impact body weight  $m$ , impact body velocity at the moment of impact with the surface  $v$ , indenter ball radius  $R$ , and its modulus of elasticity  $E_b$ . To solve different measuring tasks, different impact device are used, with different impact body weight, impact velocity, indenter ball radius and material, corresponding to different Leeb hardness scales. Impact device parameters for different scales are standardized in [4].

The advantage of Leeb hardness testers is simplicity of measurements. Large area of the indentation reduces the effect of grain, surface layers and surface roughness on measurement dispersion. Availability of international standards [4] and primary hardness standard machines [7],[8] affords to provide metrological traceability per Leeb scales. Different types of impact device is utilized for specific application range. Leeb hardness testers are used to control the hardness of machine parts, process equipment, pipelines, pumps, turbines, etc. The limitation of the method is that the thickness and mass of the sample can affect the measurement result. At the time of contact with the surface of the test specimen the falling impact body transmits part of the energy to it. In case of insufficient thickness or weight of the sample, part of the energy can be spent on the excitation of oscillations in the sample, resulting in loss of energy and reduction of impact body rebound velocity, which in turn affects the measurement result. The minimum weight and thickness values of a sample are specified in all applicable method standards for each type of impact device. In case the test sample does not meet the requirements, heavy support and/or coupling to a solid object is required. Leeb hardness measurement method is standardized on the national and international level: DIN 50156 (1-3), ASTM A956, ISO 16859 (1-3).

### 3. Ultrasonic contact impedance (UCI) hardness testers

The UCI method is based on the resonance frequency shift of the elastic element (rod) with attached indenter (Vickers diamond pyramid), forced into the surface of the test sample (Figure 3).

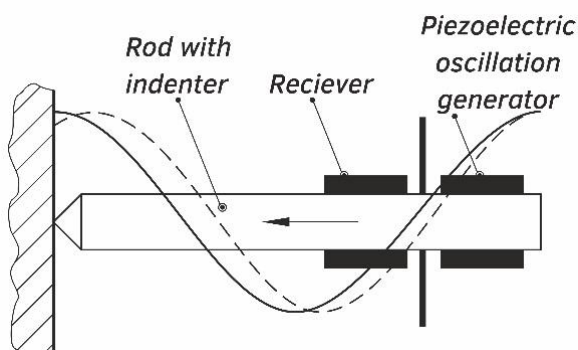


Figure 3. UCI measurement scheme.

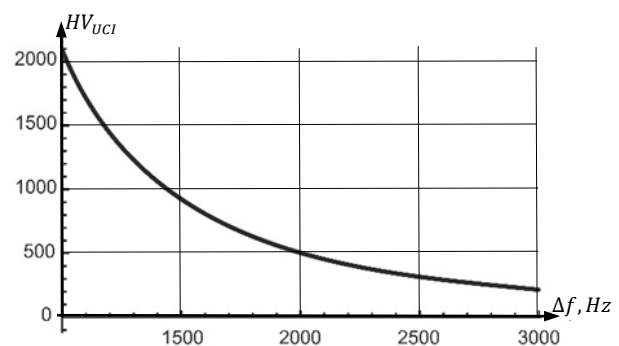


Figure 4. Calibration curve  $HV_{UCI}(\Delta f)$ .

When the diamond is indented into the test sample, the vibration frequency of the rod increases as the area of contact between the indenter and the surface increases. When the maximum load is reached (1, 5 or 10 kg depending on the modification of the measuring probe), the frequency shift  $\Delta f$  is

measured. Hardness values  $HV_{UCI}$  are determined based on the calibration curve  $HV_{UCI}(\Delta f)$  (Figure 4).

To assess the effect of the test sample material properties on the measurements of UCI tester, we shall analyse the dependence of the frequency of the self-oscillating system based on the rod with the indenter (ultrasonic resonator) as a frequency-setting element on the additional stiffness due to the contact area of the indenter with the sample material. To simplify the solution, we shall reduce the problem to a system with lumped parameters: reduced mass  $m$ , spring stiffness  $k_0$ , additional stiffness  $\Delta k$  (Figure 5). Resonance frequency of free oscillations for such system shall be:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{k_0}{m}}.$$

The effect of additional contact stiffness  $\Delta k$  considering its small value, compared with the stiffness of the whole system ( $\Delta k \ll k_0$ ) is described by the equation:

$$\Delta f = \frac{f_0}{2k_0} \Delta k. \quad (2)$$

The stiffness of the contact area is described by the equation [1]:

$$\Delta k \approx \frac{2}{\sqrt{\pi}} E^* \sqrt{A}, \quad (3)$$

where  $A$  is the projected area of contact of the indenter with the surface,  $E^*$  - the reduced plane strain modulus (1). Vickers hardness is determined by the following ratio  $HV = P/A_s$ , where  $A_s$  is the surface area of the indenter penetrated into the surface. For Vickers indenter (a tetrahedral pyramid with  $136^\circ$  angle between opposite faces)  $A = 0,927A_s$ , hence  $A \approx 1,079(P/HV)$ . Taking into account this ratio, from equations 2 and 3 we obtain the dependence of the measured UCI hardness tester values of Vickers hardness on the material properties and parameters of the ultrasonic resonator:  $HV_{UCI} = \frac{1,079}{\pi} \left(\frac{f_0}{k_0}\right)^2 P \left(\frac{E^*}{\Delta f}\right)^2$

Since,  $f_0$  и  $k_0$  are instrument characteristics and do not change in the process of measurements, this equation can be represented as:

$$HV_{UCI} \sim P \left(\frac{E^*}{\Delta f}\right)^2$$

The obtained assessment is the same as the solution given in the article [9]. It follows from this equation that the calibration of ultrasonic hardness testers should be carried out on reference test blocks made of material with the same modulus of elasticity as the tested samples, or an appropriate correction should be applied. In general, factory calibration is performed using reference test blocks made of non-alloy or low-alloy steel, therefore, in the case of the control of products made of other materials, it is required to perform calibration of the instrument on samples of tested material.

Hardness testers implementing UCI method are widely used as a portable replacement of stationary hardness testers. In case of application of 1 kg load probes, portable UCI hardness testers produce an indentation of small size and depth, which allows performing measurements of relatively thin coatings, but also raise requirements to surface preparation and material structure (roughness shall not exceed 30% of the indentation depth). Besides, UCI hardness testers are often used to control the heat affected zone (HAZ) of welded joints. Application of ultrasonic hardness testers has a number of limitations. The minimum thickness of the test sample shall exceed 15 mm. In case of failure to comply with that requirement the material can resonate and produce sympathetic oscillations (for instance, thin sheets, pipes, etc.). This problem can be solved by placing the test sample on a heavy

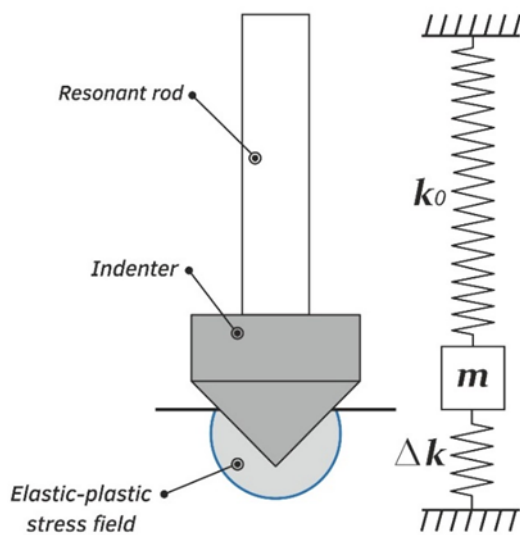


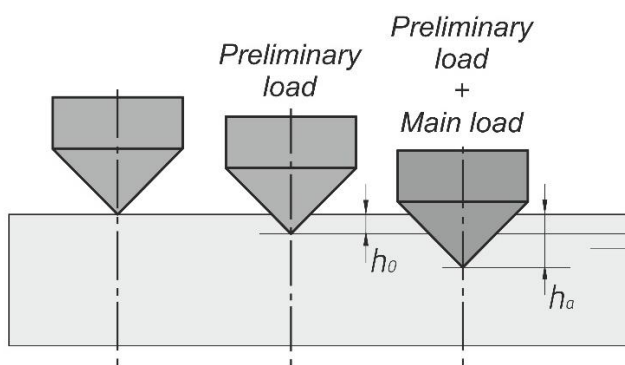
Figure 5. UCI model

metal base, connecting them with viscous paste, lubricant or oil film sufficient to damper elastic oscillations. However, even with the use of such fittings, the thickness of the product less than 2-3 mm is unacceptable. The samples less than 300 grams can go into self-oscillation mode in the process of UCI test, which imposes a limit on the minimum weight of the test sample. UCI method measurements are standardized by DIN 50159 and ASTM A1038.

#### 4. Portable Rockwell hardness testers

Portable Rockwell (PR) method is based on the measurement of the indentation depth under static load. Similar to the method of hardness measurement per Rockwell scales, the defined preliminary load (minor load) is applied, followed by main load (major load) (Figure 6).

At the time of preload application, the penetration depth of the indenter  $h_0$  into the test sample is measured. After main load application, the system is held under load for a short time, with subsequent measurement of indenter penetration depth  $h_a$  into the material. Then the difference in the indenter penetration depth  $\Delta = h_a - h_0$  is determined, which is converted into hardness values. The applied load comprises 1 kg for preload and 5 kg for main load. Diamond truncate cone with  $100^\circ \pm 0.5^\circ$  cone angle and a flat area diameter of  $0.06 \text{ mm} \pm 0.005 \text{ mm}$  is used as indenter in PR probes for soft metals, and a sharp cone-shaped indenter with  $100^\circ \pm 0.5^\circ$  angle is used for hard metals. The sharp indenter allows extending the probe operating hardness range. Because the method is static, it does not have limits common to Leeb or UCI methods. Hardness values, measured by PR method, are close, but not fully in line with *HRA* and *HRC* hardness scales. These scales differ in the geometry of the indenter (cone with  $120^\circ$  angle) and applied loads (60 and 150 kg, respectively). At the same time, the measured hardness values will be as close as possible to "true" Rockwell hardness values in case of PR hardness testers calibration using Rockwell test blocks. PR measuring probe are suitable for measuring hardness of small, light, thin, thin-walled or tubular test objects, as well as for measuring the hardness of massive machine parts. Compared with the previously described methods, PR method characterized by higher time consumption of test process, as well as inability to carry out measurements in hard-to-reach places. The thickness of the test specimens shall be 10 times greater than the indentation depth. PR method measurements are standardized by DIN 50157-1:2008 and ASTM B724-00(2006).



**Figure 6.** Measurement of Portable Rockwell hardness tester

#### 5. Portable hardness testers application problems and their solutions

The following issues inevitably arise in the course of portable hardness testers application:

1. Is it acceptable to use this type of hardness tester for a specific application?
2. How do portable hardness tester measurements correlated with the standardized hardness scales values?

The answer to the first question can usually be found in the operating instructions. Manufacturers describe in sufficient detail the restrictions related to thickness, weight, surface quality requirements and other properties of tested samples. The answer to the second question is much less obvious, despite the fact that the instrument programs easily allow displaying readings in units of different hardness scales (*HB*, *HV*, *HRx*, etc.). As it is shown above, the result of measurements by Leeb and UCI hardness testers depends on the elastic-plastic properties of tested material and the parameters of

the measuring probe itself. It is possible to obtain the measurement result in standardized scale values having calibrated the instrument on reference test blocks of this scale. However, it should be remembered that the instrument readings during measurements, will be correct only in case the reference test blocks used for the instrument calibration are made of material with the same modulus of elasticity. This requirement does not always meet in practice. Leeb or UCI hardness tester, calibrated using reference test blocks made of a particular steel grade will produce incorrect results for duralumin, bronze and even steel of other grades. The correction in compliance with the standard reference data for Young's modulus can also provide unsatisfactory result [10], which can be explained by the discrepancy between reference and real values. The situation becomes even more complicated when the hardness tester is calibrated using reference test blocks of one scale (for instance, *HB*), and the user sets the display output in another scale units (for instance, *HRC*). In this case, the conversion from one scale to another is based on the conversion tables or equations stored in memory. A number of such conversion tables and equations are provided in ASTM E140 and ISO 18265, each defined for a specific material or class of materials. In case the hardness tester calibration is not performed using appropriate reference test blocks, and the conversion table is taken for another material, the measurement result can be arbitrarily far from the real value.

The hardness measurement methods implemented by portable hardness testers do not meet the standards for conventional hardness scales. The results of portable hardness testers measurement are not the true values of these scales, but depend on the calibration of the instrument and the conversion tables used for conversion between the scales. The most effective and comprehensive way to solve this problem, according to the authors, is international standardization of hardness scales of portable hardness testers. The example of such standardization is development of an international traceability chain for Leeb scales, including the adoption of standards for the scales themselves [4], hardness testers calibration procedures [5] and hardness reference test blocks [6], as well as development of national primary references [7],[8]. The availability of such a system allows specifying requirements for materials hardness in Leeb values in the technical documentation, which will automatically eliminate the problems that are described above. In cases when, for one reason or another, it is required to determine the hardness in traditional scales, the calibration of the hardness tester shall be carried out using test blocks made of the same material, certified per required scale. In all other situations, the results of measurements obtained using portable hardness testers should be treated with caution and, if possible, checked for accuracy on test samples in the laboratory.

Complex use of various portable hardness testers can significantly expand the range of materials and objects for hardness measurement. In particular, there are practically no restrictions on the thickness and weight of the test sample for PR measuring probe. By measuring the hardness of a thin-walled pipe, for example, with this probe, it is possible to determine the correction factor for measurement results obtained using Leeb method, for which the wall thickness is a serious limitation. Similarly, the user can refine the correlation dependences between different hardness scales for materials lacking standardized conversion tables.

## 6. Conclusion

Portable hardness testers allow solving a wide range of problems of mechanical properties control of materials, products and structures in the process of their manufacturing and operation. At the same time, their application requires understanding of the advantages and limitations typical for different types of measuring probes. When selecting a hardness tester, it is required to take into account the influence of the properties of the test objects on the measurement results. Complex use of various probes can compensate for the influence of affecting factors and improve the accuracy and reliability of hardness measurements.

## References

- [1] Fischer-Cripps A C 2007 *Introduction to Contact Mechanics*, 2nd ed. (US: Springer) p 226
- [2] Leeb D 1979 Dynamic hardness testing of metallic materials *NDT International* **12(6)** pp 274-8

- [3] Johnson K 1985 Dynamic effects and impact. In *Contact Mechanics* (Cambridge: Cambridge University Press) pp 340-373
- [4] ISO 16859-1:2015(E) "Metallic materials - Leeb hardness test - Part 1: Test method".
- [5] ISO 16859-2:2015(E) "Metallic materials - Leeb hardness test - Part 2: Verification and calibration of the testing devices"
- [6] ISO 16859-3:2015(E) "Metallic materials - Leeb hardness test - Part 3: Calibration of reference test blocks
- [7] Herrmann K 2007 Reference measuring instrument for calibration of Leeb-hardness Physikalisch-Technische Bundesanstalt. Scientific news from division 5, review of the Annual Report [http://www.ptb.de/en/org/5/nachrichten5/archiv/2007/nachrichten5\\_2007.htm](http://www.ptb.de/en/org/5/nachrichten5/archiv/2007/nachrichten5_2007.htm)
- [8] Wei Shi, Wu Zeng and Qingzhong Li 2012 Leeb Hardness Standard with Laser Measuring XX IMEKO World Congress Metrology for Green Growth, Busan, Republic of Korea
- [9] Krautkrämer J and Krautkrämer H 1990 Ultrasonic Testing by Determination of Material Properties *Ultrasonic Testing of Materials* (Berlin, Heidelberg: Springer) pp 528-550
- [10] Junek M, Janovec J and Ducháček P 2017 Dependence of ultrasonic contact impedance hardness on Young's modulus of elasticity of creep-resistant steels *Acta IMEKO* **6(1)** article 5
- [11] Limanskiy D V, Vasilyeva M A 2018 Application of georadiological subsurface sensing for hydrogeological monitoring, *Journal of Physics: Conference Series* 1118(1) 012023