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TRACEABILITY OF INDUSTRIAL ROCKWELL, BRINELL, VICKERS AND KNOOP HARDNESS MEASUREMENTS

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Abstract – The measurement of hardness is used extensively by many of the world's manufacturing industries. The conventional hardness tests are the most commonly used methods for acceptance testing and production quality-control of metals and metallic products. For these industries to be successful, it is important that measurements made by suppliers and customers agree within some practical limits. Measurement traceability is a key factor in assuring hardness measurement agreement. This paper discusses the traceability issues related to the measurement of conventional hardness, including calibration, verification and uncertainty.

Keywords: hardness, traceability, uncertainty

1. INTRODUCTION

Hardness is not a fundamental property of a material. It is an ordinal quantity [1] that can only be measured by following defined test method procedures. There are no intrinsic artifacts to reference or alternative measurement systems to directly or independently measure the hardness. In this paper, we contend that, for the conventional hardness tests (i.e, Rockwell, Brinell, Vickers and Knoop), hardness measurement traceability can be achieved through two different paths of calibration-chains: (1) the calibration-chains of the machine components contributing to the test result and (2) the repeating calibration-chain sequence of calibrated primary reference test blocks used to calibrate a hardness calibration machine, which is used to calibrate the next level of reference test blocks that are used to calibrate the user's hardness machine. It is possible to achieve hardness measurement traceability by either of the two paths; however, there are advantages and disadvantages to each path depending on your level in the calibration hierarchy [1].

2. CALIBRATION AND VERIFICATION

As the conventional hardness tests gained widespread usage through history, associated test method standards were developed to standardize the tests. The conventional hardness test method standards published by the International Organization for Standardization (ISO) [2][3][4][5] and ASTM-International (ASTM) [6][7][8] use the terms "calibration" and "verification" based primarily on historical usage. These conventional hardness test method standards specify requirements and procedures that include evaluating individual components of the hardness machine, referred to as "direct verification," and using reference standards (test blocks) to evaluate the overall measurement capability of the hardness machine, referred to as "indirect verification."

According to the 2008 edition of the International Vocabulary of Metrology (VIM3) [1]:

Metrological traceability *- property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.*

Consequently, in order to achieve traceability, there has to be an unbroken chain of calibrations, that is, a sequence of calibrations from a reference to the final measuring system, where the outcome of each calibration depends on the outcome of the previous calibration, which defines a calibration hierarchy [1]. However, a calibration chain is not immediately evident from the terminology used in the standard methods. To sort this out, we need to examine the "direct verification" and "indirect verification" processes, and determine whether these can be considered calibrations based on the VIM3 definitions.

2.1 Direct verification

The conventional hardness test result is dependent on a defined measurement procedure requiring multiple and sometimes simultaneous measurements of different quantities during the testing process. For example, during a Rockwell hardness test, the hardness machine applies two levels of force to the indenter as it penetrates the test sample; measures the indentation depth; controls the rate or velocity of indentation; and measures the time period over which the force is held constant. The measurement quantities of force, length, time, and velocity, as well as other influence factors, can each influence the hardness result.

The test method standards specify requirements for the components of the hardness machine having the most significant influence on the hardness result. Procedures are given to measure these components, and permissible limits on the measurement results are stated as criteria for being in compliance with the standard. This process is termed a "direct verification", but is it actually a calibration, a verification or both?

According to the VIM3, the terms calibration and verification are defined as:

Calibration *- operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication.*

NOTE 1 A calibration may be expressed by a statement, calibration function, calibration diagram, calibration curve, or calibration table. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty.

NOTE 2 Calibration should not be confused with adjustment of a measuring system, often mistakenly called "self-calibration", nor with verification of calibration.

NOTE 3 Often, the first step alone in the above definition is perceived as being calibration.

Verification *- provision of objective evidence that a given item fulfils specified requirements.*

For the purpose of achieving traceability, it is reasonable and useful to consider that the specified "direct verification" process is, in fact, a verification based on calibration results. A calibration of each machine component is made first, and then the calibrated component is validated as being suitable for use by verifying that the calibration results are within the stated permissible limits. Keep in mind that the validity of a calibration result is independent of whether it passes a verification test in accordance with the test method standard.

It is useful to consider this a two-step process of calibrations followed by verifications because it provides a traceability chain of calibrations for those component measurements that are made as part of the hardness test, such as the force and indentation size measurements. However, it may not be apparent that all of the measurements of machine components meet the definition of a calibration according to the VIM3. It is reasonable that the "direct verification" measurements of those machine components that make subsequent measurements during the hardness test (e.g., force measuring load-cell, depth-measuring dial gage, indentation-diagonal measuring microscope, etc.) be considered calibrations since each of these components exhibits indications. However, it is less clear for those components that appear not to provide measurement indications during a hardness test, such as the indenter and weights that apply force. The VIM3 addresses this in the definitions, examples and notes of "material measure" and "indication" as follows:

Material measure *- measuring instrument reproducing or supplying, in a permanent manner during its use, quantities of one or more given kinds, each with an assigned quantity value.*

EXAMPLES Standard weight, volume measure (supplying one or several quantity values, with or without a quantity value scale), standard electric resistor, line scale (ruler), gauge block, standard signal generator, certified reference material.

NOTE 1 <u>The indication of a material measure is its assigned quantity value.</u>

Indication *- quantity value provided by a measuring instrument or a measuring system.*

NOTE 1 <u>An indication may be</u> presented in visual or acoustic form or may be transferred to another device. An indication is often given by the position of a pointer on the display for analog outputs, a displayed or printed number for digital outputs, a code pattern for code outputs, or <u>an assigned quantity value for material measures.</u>

It can be concluded from these definitions that each of these other machine components, such as the indenter and weights, can be considered material measures, and their assigned quantity values are the indications. This fulfills the first part of the definition of calibration. For example, in the case of measuring the tip radius of a Rockwell diamond indenter using a stylus instrument by measuring displacements in 2 axes as the stylus moves across the diamond surface, the calibration definition could be re-written as, "… *establishes a relation between the quantity values with measurement uncertainties provided by* <u>the stylus instrument</u> *and* <u>the</u> *corresponding* <u>assigned radius value</u> *with associated measurement uncertainties* ..." In this case, the measurement is a one-point calibration where the calibrated stylus-instrument is the measurement standard and the indication is the assigned radius value. The relation is established by the calibration process.

If all significant influence quantities of machine components can be identified and measured, then it is reasonable to conclude that hardness measurement traceability can be achieved through the multiple calibration chains for each of these machine components to the International System of Units (SI), with measurement uncertainty determined by combining the individual uncertainties of the machine components.

2.2 Indirect verification

Due to the difficulty at the industrial level in identifying all of the influences to the hardness result, a process for evaluating the overall measurement capability of the hardness machine was integrated into the test method standards. This process uses reference standards (test blocks) to validate a hardness machine, which can then be used to assign values to lower-level reference standards, which, in turn, can be used to validate lower-level hardness machines. The test method standards refer to the repeating two steps in this process as "indirect verification" of the hardness machine and "calibration" of reference test blocks. If this process is actually a repeating chain of calibrations of reference blocks and hardness machines, then it is reasonable to conclude that hardness traceability should be achievable by this path.

The "indirect verification" step of validating the hardness machine using reference blocks clearly meets the VIM3 definition of calibration. The quantity values of the reference blocks are compared to the indications of the hardness machine. For the second step of assigning a value to a reference block, again we have a situation where measurement indications are not provided by the test block during the "calibration" process. However, similarly as discussed above for other material measures, the indications are the assigned quantity values allowing this process to meet the definition of a calibration. Therefore, an unbroken chain of calibrations is in place from the top reference to the measurement.

Although this may be the most viable path for achieving traceability, there are issues that have to be considered. The conventional hardness test method result is material and hardness-level dependent. In other words, if a hardness machine is calibrated using a reference block of a specific material and at a specific hardness level, the calibration results do not necessarily ensure good measurement results on other materials or at other hardness levels. The test method standards have instituted practical requirements to calibrate and verify a hardness machine using reference blocks that sample different hardness levels, indentation depths, applied forces and the types of indenters to be used. This calibration scheme is considered acceptable for assuring that a hardness machine is suitable for use. However, this chain of calibrations, by itself, does not prevent the situation of errors offsetting other errors. This can allow the calibration results to pass the verification requirements even when some machine components are outside permissible operating limits, thus underestimating the true uncertainty. The consequence of this is that a true measurement uncertainty is not being determined, but instead it is an estimated uncertainty.

3. HARDNESS REFERENCE VALUE (DEFINITION)

Conventional hardness methods have evolved over the past 100 years initially based on the test method standards published by national and international Standards Development Organizations, such as ASTM and ISO. The test methods specify calibration procedures and acceptability verification limits based on higher level standards. However, the highest level of reference value went no further than the National Metrology Institutes (NMI) or, in some cases, secondary calibration laboratories without a clear link between countries or regions. This changed in 1999 with the establishment of the Working Group on Hardness (WGH) in the framework of the Consultative Committee for Mass and Related Quantities (CCM) of the International Committee of Weights and Measures (CIPM) [9]. The CCM-WGH has the responsibility to examine hardness influence parameters and to propose improved international definitions of the hardness tests for NMI use. These hardness definitions are now recognized as the top level of the hardness traceability chain, with compatibility between NMIs verified through international hardness measurement comparisons (Key Comparisons), as shown in Fig. 1.

Currently, the CCM-WGH has only defined the parameters of the Rockwell C scale (HRC); however, efforts are now underway to expand the definitions development to the other Rockwell hardness scales, Brinell hardness and Vickers hardness. Until this is accomplished, the traceability

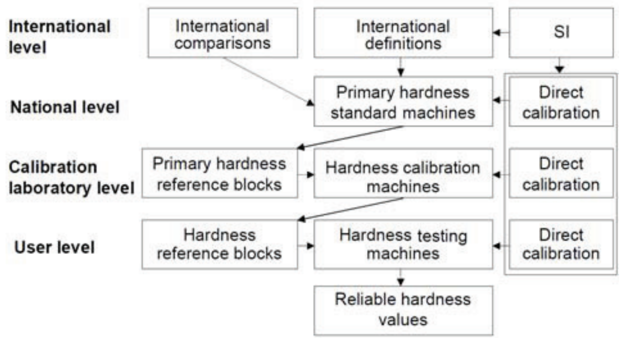

Fig. 1. Conventional hardness calibration chains

for these hardness scales will continue to be to the NMI and its own definitions, or to another high–level standard.

4. CONVENTIONAL HARDNESS TRACEABILITY

As discussed above, for the conventional hardness tests, there are two paths for measurement traceability with multiple calibration chains, as illustrated in Fig. 1. We consider both paths to be valid, however, each has advantages and disadvantages. Depending on the level of the calibration hierarchy, it can be argued that only one of these paths may be needed, or perhaps both paths are needed. If both paths are needed, that leads to the question of how measurement uncertainty is to be determined. This issue is better understood by examining the different levels of the traceability chain separately.

4.1 National level

At the National level, with NMIs standardizing national hardness scales using primary hardness standard machines, there is only one traceability path choice. Since there is no single internationally recognized reference artifact for the conventional hardness scales, traceability can only be achieved through the calibration of the machine components to the International System of Units (SI). An NMI has the advantage of ordinarily having the time, funds and capabilities to thoroughly evaluate their measurement systems and identify all significant influence quantities for determining measurement uncertainty. The NMI also has the advantage that their calibration measurements are usually conducted on a single material depending on the hardness scales, and usually only for a select number of hardness levels for calibrating primary reference blocks. The measurement uncertainty analysis can then be focused on specific hardness levels, and material dependency issues are eliminated.

4.2 Calibration level

At the Calibration laboratory level, the measurement traceability issues become more complicated since many levels of hardness scales are usually calibrated and in some cases multiple materials may be used for reference blocks of the same hardness scale level. The test method standards require that the calibration hardness machine be calibrated through both types of calibration chains; calibration of machine components and calibration using reference blocks. Therefore, separate traceability paths are being achieved for the individual machine component's measurement quantities, and hardness measurement traceability is being achieved by the reference block calibration chain.

Although not commonly done, it is certainly possible for a calibration laboratory to determine hardness measurement uncertainty through the machine component calibrations as is done by NMIs. This is likely most difficult for the Rockwell hardness test, which has a more complicated measurement system, but could reasonably be done for the Brinell, Vickers and Knoop hardness tests. However, in most cases, a hardness calibration laboratory does not have the resources available to sufficiently identify and evaluate all influence quantity values and their associated uncertainty contributions for all the hardness levels and materials that are calibrated. Also, these influence quantities are generally not in units of hardness, such as for force or length measurements. Determining the relationship between the influence quantities and the effect on the hardness measurement value is a difficult undertaking, often requiring extensive experimentation.

Thus, in most cases, the use of primary reference block standards is the most reasonable path to determine hardness uncertainty for these calibration laboratories. An advantage of basing uncertainty on this calibration chain is that the uncertainty parameters are in hardness units. It is crucial, however, that the calibration laboratories frequently calibrate the hardness machine components to ensure that significant errors are not being offset by other errors. This is important since primary reference blocks are usually only available for limited hardness levels. As discussed above, the uncertainty values determined by the reference block calibration chain path are only estimations, and ensuring that the machine components are performing well within the permissible limits helps to improve the uncertainty determination, particularly at hardness levels other than the levels of the available reference blocks.

4.3 User level

At the User level, practical issues become increasingly important. Typical hardness users have few resources or capabilities to assess the influence quantities of their hardness machines. In fact, users usually contract a calibration agency to perform the calibrations of the machine components by "direct verification", although the need for this rarely occurs since the test method standards essentially only require these calibrations and verifications when a hardness machine is new or has undergone an adjustment or repair. An additional issue is that a user often tests samples of many different materials over a wide range of hardness levels. Thus, the most practical method of achieving hardness measurement traceability and determining hardness measurement uncertainty is through the reference block calibration chain. Although there is a risk that the uncertainty will be underestimated due to errors offsetting other errors, it is not practical to expect the user to be able to accomplish this through the calibrations of the machine components.

The discussion up to now has assumed that hardness measurement traceability is achieved to the CCM-WGH hardness definition through the nation's NMI, or to the NMI's hardness definition for those hardness scales that the CCM-WGH has not defined. However, the current situation for many of the world's NMIs is that not all hardness tests and hardness scales are being standardized. In these cases, it is not clear to what standard the hardness traceability should be made. In some countries, the secondary calibration laboratories maintain their own hardness standards, which are rarely linked to the standards of other countries. Should the Calibration level laboratories be expected to shop the world's NMIs to obtain the needed primary reference blocks? These issues are beyond the scope of this paper, but should be resolved by the CCM-WGH.

5. SUMMARY

The hardness test method standards refer to the procedures for assuring that the hardness machine is suitable for use as "direct verification" and "indirect verification," however, it is calibration measurement results that are being verified. These procedures provide two paths of calibration-chains for achieving hardness measurement traceability. The calibration chain hierarchy level determines which path is the most practical to follow. There is a need for additional progress by the CCM-WGH in defining the hardness scales and for establishing acceptable highest level standards in the calibration chain hierarchy.

REFERENCES

[1] VIM3, *International vocabulary of metrology — Basic and general concepts and associated terms*, issued by the Joint Committee for Guides in Metrology member organizations (BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML), [www.bipm.org], 2008

[2] ISO 6508 Parts 1,2 &3 2005 Metallic Materials—Rockwell Hardness Test (Geneva: International Organization for Standardization)

[3] ISO 6506 Parts 1,2,3&4 2005 Metallic Materials—Brinell Hardness Test (Geneva: International Organization for Standardization)

[4] ISO 6507 Parts 1,2,3&4 2005 Metallic Materials—Vickers Hardness Test (Geneva: International Organization for Standardization)

[5] ISO 4545 Parts 1,2,3&4 2005 Metallic Materials—Knoop Hardness Test (Geneva: International Organization for Standardization)

[6] ASTM E18-08b 2008 Standard Test Methods for Rockwell Hardness of Metallic Materials (West Conshohocken, PA: ASTM International)

[7] ASTM E10-08 2008 Standard Test Method for Brinell Hardness of Metallic Materials (West Conshohocken, PA: ASTM International)

[8] ASTM E384-10e2 2010 Standard Test Method for Vickers and Knoop Hardness of Materials (West Conshohocken, PA: ASTM International)

[9] A. Germak, K. Herrmann and S. Low, "Traceability in hardness measurements: from the definition to industry", *Metrologia,* vol. 47, pp. S59-S66, 2010.