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EVOLUTIONS IN HARDNESS SCALES DEFINITION

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Abstract – A conventional characteristic of hardness measurements is the strong dependency on the official definition of each scale. For this reason, and to assure a good connection between National Metrology Institutes (NMIs), scientific organizations (e.g., IMEKO[1]) and international organizations for standardization (e.g., ISO[2] and OIML[3]), a new Working Group on Hardness (WGH) was created a few years ago under the Consultative Committee for Mass and Related Quantities (CCM) of the Comité International des Poids et Mesures (CIPM).

One of the principal aims of the WGH is to analyze the level of accuracy corresponding to the state-of-the-art of national primary standards, ultimately leading to improvements in the hardness scale definitions and, at the same time, providing well-defined traceability, in terms of uncertainty, of industrial measurements. Recent efforts to improve hardness scale definitions and the consequential reduction of uncertainty are presented in this paper. Contributing to this effort are the NMIs that currently maintain hardness standards and those that have plans to realize them in the near future. By improving the definitions and the associated uncertainty, certain advantages will be obtained at all levels in the dissemination of hardness standards: from the calibration and testing laboratories to industrial measurement applications.

Keywords: hardness scales, definitions, uncertainty

1. INTRODUCTION

In figure 1 the structure of the metrological chain for the definition and dissemination of hardness scales is shown. It starts from the international definitions of the different hardness scales, which are materialized by a number of national primary hardness standard machines [1, 2]. Dissemination of the hardness scales is accomplished using primary hardness reference blocks standardized by the primary hardness standard machines. In some cases, primary hardness reference blocks are directly commercialized and used for the calibration of industrial hardness testers. More frequently, secondary calibration laboratories for verifying and monitoring their hardness calibration machines use primary hardness reference blocks. The secondary calibration laboratories then calibrate the majority of hardness reference blocks used for the calibration of the industrial hardness testers.

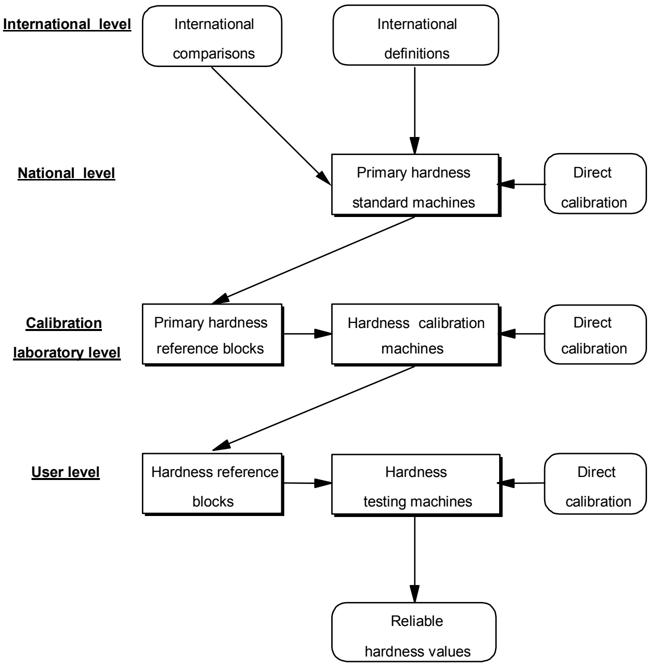

Fig. 1. The structure of the metrological chain for the definition and dissemination of hardness scales [3]

The first contribution to uncertainty of any hardness scale is the uncertainty contained in its definition and in its materialization. As with any other technological quantity, hardness scales have complex definitions, such that theoretical uncertainty evaluations are often questionable, if even possible. To help and to harmonize the uncertainty calculation of hardness measurements, a new document was recently published by the European co-operation for Accreditation (EA) [3] and a working group on uncertainty of hardness has been created in the framework of the ISO Technical Committee 164/ Sub Committee 3 – "Hardness testing". The approach given in the EA document will be

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[1] IMEKO: International Measurement Confederation
[2] ISO: International Organization for Standardization
[3] OIML: International Organization of Legal Metrology

used as the basis for calculating the uncertainty of new proposals of hardness scale definitions.

The measurement uncertainty of a hardness test is very sensitive to many parameters related to the test procedure and the function of the hardness machines. We demonstrate that the present definitions fail to identify several significant influence parameters of the hardness test and that some of the identified parameters are not metrologically well defined. In fact, one of the limits of hardness quantity is its conventional definition. At present, both secondary calibration laboratories and primary laboratories use the same definition in terms of the values of the hardness test parameters and their related tolerances. There is no doubt that, if the same levels of tolerances are kept, the same level of uncertainty will be obtained.

2. ANALYSIS

The first step in trying to improve the uncertainty produced by the definition is to improve the definition itself. The strong link and cooperation between NMIs, OIML, IMEKO and ISO gives the possibility of defining the hardness scales and determining uncertainty while, at the same time, addressing the needs of industry**.**

A great deal of past experience has been accumulated, mainly for the Rockwell C hardness scale (HRC). From this experience, we can obtain the necessary information for choosing the direction for future developments. A major source of information on uncertainty due to hardness scale definition and its materialization is given by the results obtained in independent international comparisons [4, 5, 6, 7].

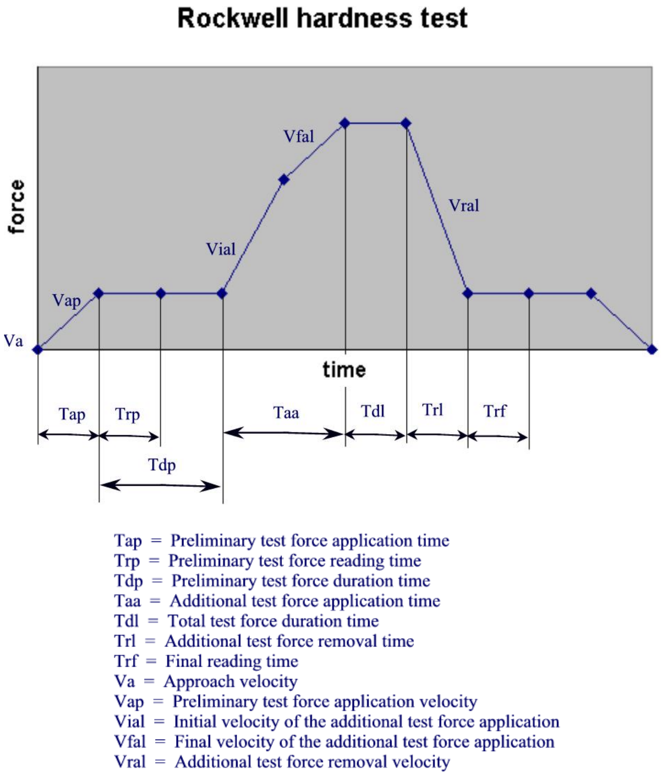

Fig. 2. Parameters involved in the Rockwell hardness testing cycle

Examining these studies and a number of subsequent international comparisons, we observe that the measurement differences obtained using a common indenter and similar indentation cycles were lower than ±0,5 HRC. These differences increased when each institute used its own indenter.

What is the problem? Why do the best hardness machines, maintained at metrological laboratories, produce such a difference in the results? These studies demonstrated that, for the Rockwell C hardness scale, the main problems connected with the practice of hardness measurement [8] are the poor definition of indentation parameters and the performance of the diamond indenter.

A comprehensive definition should give all the parameters describing the indentation cycle and all the characteristics of the indenter. The main points to be examined are the effect of the indentation velocity, the effect of the loading time (the time to increase the load from the preliminary force to the total force), the effect of the load dwell times, the effect of the indenter geometry and other effects of the indenter (fig. 2).

An analysis of the present HRC definition has been done in the framework of the CCM-WGH. At the last WGH meeting in May 2002, a new proposal for a definition to be used by the NMIs was presented and analysed (Table I). The goal is to harmonize Rockwell hardness to ±0.2 HRC.

TABLE I. Proposal for reference values of the main parameters involved in the Rockwell hardness test

HRC Test parameters		*HRC Reference value*	*Start measurement*	*Stop measurement*
Preliminary test force application time (T_{ap})	$T_{pl} = \frac{T_{ap}}{2} + T_{rp}$	3 s	1% of the preliminary test force	99% of the preliminary test force
Preliminary test force reading time (T_{rp})			99% of the preliminary test force	Reading
Total test force dwell time (T_{dl})		4 s or 5 s	99% of the total test force	99% of the total test force
Final <u>mean</u> velocity of the additional test force application (V_{fal})		0,030 mm/s	80% of the total test force	99% of the total test force
Temperature of test (T)		23°C	-	-
Preliminary test force value (F_0)		9,80665 N	-	-
Additional test force value (F_1)		1372.931 N	-	-
Average radius spherical tip (R_a)		0,200 mm	-	-
Average cone angle (α_m)		120°	-	-
Elasticity (e)		?	-	-

The WGH members generally agreed with most of the parameter reference values; however, the need for having tolerances at the primary level was questioned. Many WGH-CCM members felt that only reference values should be defined (Table I.), leaving deviations from the values to be reflected in each NMIs' stated uncertainty value. There will be further discussion of the reference values and tolerances at the next meetings.

Also discussed was the need for better agreement in the performance of Rockwell indenters used by NMIs. Two possible solutions were discussed: developing a procedure for verifying the performance of Rockwell hardness indenters and possibly defining a single source or collection of well-characterized Rockwell diamond indenters for the sole use of NMI Rockwell hardness standardizing laboratories.

2.1. Uncertainty evaluation

When the definitions become harmonized, it will be possible to evaluate the uncertainty in the realization of hardness scales at the NMI level following the Guide to the Expression of Uncertainty in Measurement (GUM) specifications [9]. By considering Rockwell hardness H as the measurand (dependent variable), it can be represented as a function of the independent measurement variables. Taking into consideration only the most important parameters, it is possible to write the following function,

$$H = f\,(F_0;\ F_1;\ R_a;\ \alpha_m;\ t_{pl};\ t_{dl};\ v_{fal};\ h;\ N) \qquad (1)$$

where h is the indentation depth, N is a constant number dependent on the Rockwell hardness scale (the other symbols are defined in Table I). Using the appropriate sensitivity coefficients, it is possible to obtain the formula for evaluating the uncertainty propagation (in the approximation of uncorrelated independent variables),

$$u^2(H) \approx \sum_{i=1}^{N} u_i^2(H) = \sum_{i=1}^{N} c_i^2 u^2(x_i) \qquad (2)$$

Examples of this calculation are reported in the EA document [3].

The problem is that the sensitivity coefficients are known only for the most important parameters and only for the most commonly used hardness scales. Since most of the sensitivity coefficients can be calculated only using experimental factorial plans, a substantial request will be made to the scientific community to investigate the influences of the different parameters and to calculate the sensitivity coefficients for all of the major parameters of every hardness scale. Once this task is completed, every NMI will be able to easily calculate the uncertainty in the realization of their hardness scales and of their hardness block calibrations.

To calculate the uncertainty in the realization of hardness scales, one should also add the repeatability, the reproducibility and the long term stability of the primary hardness standardizing machine to the contributions of the uncertainty calculated in (2).

The calibration of a hardness block involves the determination of the mean hardness value of the surface of the block by making five or more hardness measurements over the testing surface. Being that hardness measurements are, strictly speaking, destructive measurements (it is not possible to repeat the measurements exactly in the same position on the block surface), the standard deviation of the mean value will also take into consideration the non-uniformity of the hardness block. The uncertainty in the certified value of primary hardness reference blocks may be evaluated by combining the standard deviation of the mean value of the hardness block with the uncertainty in the realization of the hardness scale. The same calculation procedure should be followed to evaluate the calibration results obtained during international comparisons.

3. FUTURE

Using this approach for the other hardness scales, it should be possible to produce reference levels having minimum uncertainty, a very useful achievement for every scientific and industrial activity. In fact, many of the effects which influence Rockwell measurement results also occur in Brinell and Vickers hardness tests, for example, the sensitivities to time under load (creep effect) and indentation velocity (strain hardening) being characteristics of the material. These effects must be combined with other peculiarities of the Brinell and Vickers hardness tests, such as the effect of the numerical aperture of the lens used for the optical measurement of the indentation.

Moreover, new scales have been standardized recently. This is the case of the Martens Hardness Scales, which has been the subject of new publications by ISO [10]. Also in this case, even if the metrological chain follows the same structure applicable to the other hardness scales (fig. 1), additional problems can arise from the definition. For instance, the definition of the zero-point, from which the penetration is calculated, is evaluated by extrapolation of fitted functions, which can give, as solutions, imaginary numbers [11]. To solve this specific problem, several proposals have been presented [11, 12], but it is again within the framework of the WGH-CCM to harmonize the parameters of the instrumented indentation test and to allow the expression of Martens Hardness uncertainty, as required by relevant standards.

4. CONCLUSION

The examination of the situation allows us to be optimistic. It appears that the technical capabilities to reduce the uncertainty in the Rockwell C hardness scale, from about ±1 HRC to ±0,2 HRC, is within the state of the art. What will be necessary is an organized effort to extract information from the past technical results given by a large number of researchers, as well as, the most recent comparisons of hardness scales and indenter measurement. Based on this information, a general agreement on measurement procedures will be developed, that is, metrological definitions of hardness scales and indenter selection.

Uncertainty evaluations taking into account the present state of the art of measurement capabilities show that, by adopting improved metrological definitions of the HRC scale, the measurement uncertainty can be significantly reduced. A cooperative international effort in the framework of the WGH-CCM is therefore necessary for studying and experimentally evaluating improved hardness definitions.

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