XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6−11, 2009, Lisbon, Portugal

STUDY OF THE BEST MEASUREMENT CAPABILITY IN ROCKWELL SCALE AT THE BRAZILIAN NMI INMETRO´S PRIMARY HARDNESS STANDARD MACHINE

Jorge Trota Filho [1], *Sérgio Pinheiro de Oliveira* [2], *Islei Domingues da Silva* [3], *Renato Reis Machado* [4], *Cláudio Afonso Koch* [5]

[1] INMETRO, Duque de Caxias, Brazil, jtfilho@inmetro.gov.br
[2] INMETRO, Duque de Caxias, Brazil, spoliveira@inmetro.gov.br
[3] INMETRO, Duque de Caxias, Brazil, idsilva@inmetro.gov.br
[4] INMETRO, Duque de Caxias, Brazil, rrmachado@inmetro.gov.br
[5] INMETRO, Duque de Caxias, Brazil, cakoch@inmetro.gov.br

Abstract − This paper shows the actual status of an on-going metrological research that aims an upgrade of the current Rockwell C hardness scale´s best measurement capability (BMC), e.g. 0.3 HRC, referred to the Primary Hardness Standard Machine installed at the Brazilian NMI INMETRO. This value complies with the ISO hardness standards and the GUM uncertainty guide as well as the main eight uncertainty sources and respective sensitivity coefficients for the direct calibration method, detailed in the EURAMET hardness guide. This work shows that an increasing knowledge of the actual calculated sensitivity coefficients yields a consequent reduction in the BMC. These experimental coefficients were estimated by the use of up to six uncertainty sources. In this case, the BMC changed to 0.17 HRC (two significant digits) or 0.2 HRC (one significant digit).

Keywords: Rockwell C hardness, hardness calibration, best measurement capability.

1. INTRODUCTION

The best measurement capability (BMC) is a very important information for all National Metrology Institutes (NMIs), since it provides the degree of closeness of the measurement uncertainty among them in performing measurements of a specific quantity. Besides, it is desirable for any National Metrology Institute (NMI) the possibility of being able to improve the BMC in a given mensurand. In other words, a good result in terms of a BMC and its registry in the BIPM´s Appendix C is an undoubtly proof an NMI has been practicing a high-quality metrology.

The EURAMET´s Guidelines on the Estimation of Uncertainty in Hardness Measurements [1], "EURAMET hardness guide", and ISO GUM 95 *Guide to the Expression of Uncertainty in Measurement* [2], "ISO-GUM", provide the necessary instructions on how to calculate the measurement uncertainty of hardness reference and testing machines as of the Primary Hardness Standard Machine, "PHSM", located at the INMETRO´s laboratorial facilities in Rio de Janeiro State, Brazil. Indeed, it should be observed the possibility of estimation of the measurement uncertainty of a reference machine from appropriate reference values [1]. However, the best way to determine the uncertainty of a HSM is by inserting in the calculations actual data on the variations of the input parameters, e.g. uncertainty sources of the process. Thus, a wise approach would be a clear description of the behaviour of the actual system in order to study an optimization of the currently used BMC.

ISO 6508-2:2005 [3] and ISO 6508-3:2005 [4] standards provide methods to be employed in order to calibrate a PHSM directly and indirectly. So, it is assumed the most important parameters of the measurement process that influence directly the process can be controlled in such a way it is possible to obtain a metrologically reliable hardness value reached at the end of the test. However, if any of the mentioned parameters of measurement process are changed within permissible values range of the related hardness standards [3,4], the other parameters will change automatically as expected. INMETRO's Hardness Laboratory has installed a Primary Hardness Standardization System, composed by the Primary Hardness Standard Machine, the Reference System for Measuring Brinell and Vickers Indentations ("Gal-Vision") and the Primary System for the Calibration of Vickers and Rockwell Indenters ("Gal-Indent").

For the calculations of the uncertainties in the low, medium and high hardness ranges, the following parameters were considered: initial force (F_o), additional force (F), internal angle of the indenter (α), indenter radius (r), the indentation depth (h), indentation velocity (ν), time of initial force application (t_o), and time of additional force application (t). However, in this work the values for the initial force and additional force were identical to those provided by EURAMET hardness guide [1], e.g. throughout this work the uncertainty sources "initial force" and "additional force" used exclusively the values referenced in the EURAMET hardness guide.

The objective of this work is to present results that may improve the measurement uncertainties values of the INMETRO´s Hardness Standard Machine. This article aims to show the studies proceeded at INMETRO for the improvement of the best measurement capability of the PHSM in the Rockwell C hardness scale.

Being specific, this study intends to create a link between the changes of variables in the process of measuring the hardness and the PHSM's Rockwell C hardness values obtained. Besides, it will be presented an analysis on what would be the PHSM´s best measurement capability for the Rockwell C hardness scale of hardness. The discussion of these parameters changes will allow the assessing of the influence of certain parameters (reference and experimental ones) on the expanded uncertainty of PHSM.

2. MATERIALS AND METHODS

For the metrologically reliable tests it was used the INMETRO´s Primary Hardness Standard Machine (metrologically characterized and qualified right after its installation in Brazil by INRiM - National Metrology Institute of Italy). Figure 1 shows a picture of part of the INMETRO´s Hardness Laboratory: the PHSM is at the left, and its controlling console is at the right. Together both systems allow the calibration of hardness reference blocks in Rockwell and Rockwell Superficial, and, by use of another standard (the Gal-Vision standard, not shown in the figure) it is possible to calibrate Brinell and Vickers hardness blocks as well.

Figure 1 – INMETRO´s Primary Hardness Standard Machine

To ensure the best results could be obtained in the hardness measurements the INMETRO´s reference diamond cone Rockwell hardness indenter was used. The chosen Rockwell C standard blocks for the indentations were fabricated by Japanese company Yamamoto with nominal hardness values in the ranges 20 to 25, 40 to 45 and 60 to 65 HRC. This experimental strategy was based on the widespread use of this hardness ranges schema (low, medium and high hardness), as defined in relevant bibliographical references on hardness metrology [1,5].

The choice of parameters for measuring the hardness took into account the best hardness measurement practices (and their associated Type-A uncertainties) established by INMETRO's Hardness Laboratory as a consequence of previous research and development work in the standardization of hardness scales.

Hardness experiments were carried out by the recommended general procedure of ISO 6508-1:2005 [5]. Accordingly, the hardness reference blocks under test were lid on the rigid support of the INMETRO´s Hardness Standard Machine, being previously cleaned with isopropyl alcohol PA in both the upper and bottom surfaces.

In analyzing the results of measuring hardness, Grubbs and Dixon rejection criteria were used for the measured hardness values, whilst the calculation of uncertainty of measurement used the procedure recommended by ISO-GUM [2].

From the existing eight parameters suggested in the EURAMET hardness guide [1] six parameters were chosen to be varied in this work (α, r, h, ν, t_o and t), whereas initial force F_o and additional force F were kept unvariable, so the reference values [1] were used in all situations detailed next. These six changed parameters originated five testing conditions, namely, C1 through C5, where:

a) C1 was the reference condition suggested by the EURAMET hardness guide [1], so none of the eight parameter values were experimental;

b) C2 was an experimental condition with the reference values [1] of both t_o and t;

c) C3 had an experimental t_o value and a reference t value;

d) C4 used a reference t_o value and an experimental t value;

e) C5 referred to both experimental t_o and t values.

As planned, in all non-reference conditions (C2, C3, C4 and C5) the sensitivity coefficients related to the parameters "α", "r", "h" and "ν" were obtained exclusively from the experiments in the PHSM.

3. RESULTS AND DISCUSSION

The indentations had clearly carried out properly, being a qualitative demonstration that the application of both initial force and additional force on the hardness reference blocks in all tests was very efficient and effective.

The several values related to the internal angle of the indenter, the indenter radius, the indentation depth, the indentation velocity, the time of initial force application and the time of additional force application were obtained from experimental data. Table 1 below shows the parameters used in each of the five studied conditions, where C1 was the reference condition (whose default values of the uncertainty contributions were represented by the capital letter R) [1] and the other four C2 through C5 conditions (whose experimental values of the uncertainty contributions were identified by the capital letter E) admitted a mixture of reference and experimental values combined in different ways, as described earlier.

The use of experimental values lead to a reduction of the PHSM uncertainty when compared to the reference values listed in the EURAMET´s Guidelines on the Estimation of Uncertainty in Hardness Measurements [1].

Table 1 – Five test conditions and respective eight controlling parameters for determining the best measurement capability in Rockwell C hardness scale for the INMETRO´s Primary Hardness Standard Machine.

Condition \Parameter	F_0 (N)	F (N)	α (º)	R (mm)	H (μm)	v (μm/s)	t_0 (s)	t (s)
C1	***R***	***R***	***R***	***R***	***R***	***R***	***R***	***R***
C2	***R***	***R***	***E***	***E***	***E***	***E***	***R***	***R***
C3	***R***	***R***	***E***	***E***	***E***	***E***	***E***	***R***
C4	***R***	***R***	***E***	***E***	***E***	***E***	***R***	***E***
C5	***R***	***R***	***E***	***E***	***E***	***E***	***E***	***E***

The Table 2 below shows the calculated values for the sensitivity coefficients studied here. As stated before, the sensitivity coefficients of the parameters initial force (Fo) and additional force (F) were obtained from EURAMET´s Guidelines on the Estimation of Uncertainty in Hardness Measurements [1] while the sensitivity coefficients related to the other parameters were estimated from experimental data related to PHSM.

Table 2 – Sensitivity coefficients of the parameters F_0, F, α, r, h e v which varied for low, medium and high hardness ranges.

X_i	a_i	$u^2(X_i) = a_i^2/3$	$C_i = dH/dX_i$		
			20-25HRC	40-45HRC	60-65HRC
F_0	0.2	0.013	0.12	0.07	0.05
F	1.5	0.75	-0.04	-0.03	-0.02
α	0.1	0.0033	1.8	0.5	-0.46
r	0.005	0.0000083	-0.037	-0.046	0.016
h	0.2	0.013	-0.5	-0.5	-0.5
v	10	33	-0.003	0.019	0.0094

In the table above, "X_i" means the studied parameter, "a_i" is the semi-interval of the retangular distribution, $u^2(X_i)$ is the variance of studied parameter, and "C_i" is the sensitivity coefficient.

For calculations of sensitivity coefficients related to time of initial force application (t_o), and time of additional force application (t) it were used semi-amplitude values of the experimental values of both t_0 and t. The Table 3 below shows the semi-amplitudes and the sensitivity coefficients for low, medium and high hardness ranges.

Table 3 – Experimental sensitivity coefficients related to times of initial force application (t_o) and additional force application (t).

Hardness ranges	t_0			t		
	a_i	u^2	C_i	a_i	u^2	C_i
20 to 25HRC	0.09	0.0081	0.28	0.06	0.0036	0.73
40 to 45HRC	0.03	0.0009	0.55	0.02	0.0004	-0.66
60 to 65HRC	0.09	0.0081	-0.21	0.07	0.0049	-0.25

Next, it will be shown the relationship between the experimental values of hardness obtained during the tests and time of initial force application. Thus, it was possible to calculate the coefficient of sensitivity in relation to the time of application of the initial force in low, medium and high hardness ranges, shown in figures 2A, 2B and 2C, respectively.

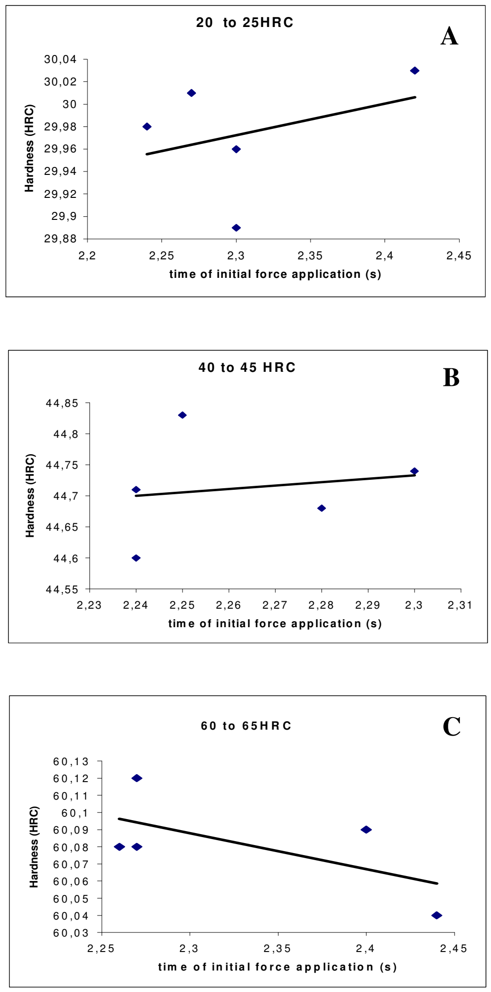

Figure 2 – The relationship between time of initial force application and hardness experimental values.

The graphs of Figure 3 show the results for the sensitivity coefficients in relation to the time of application of the additional force. The figures 3A, 3B and 3C represent the behavior of the hardness scale on the time of application of the additional load for low, medium and high hardness ranges.

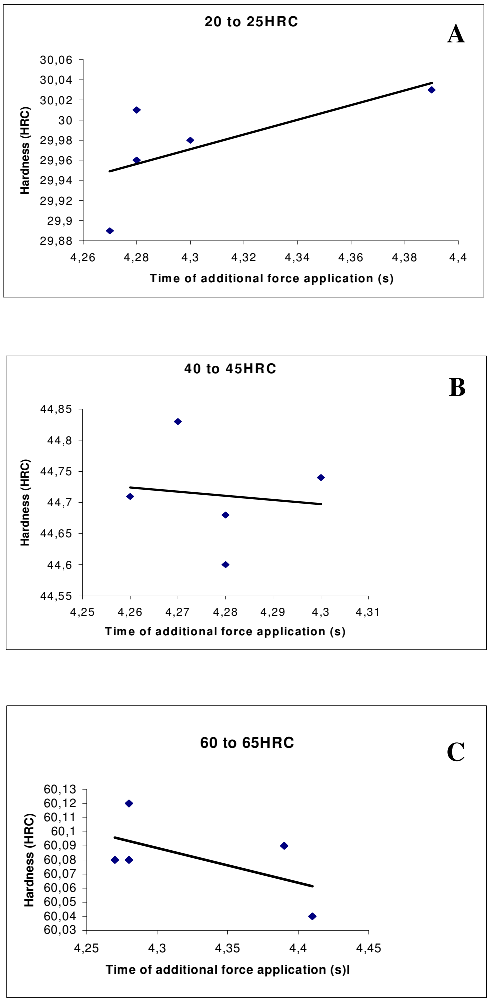

Figure 3 - The relationship between time of additional force application and hardness experimental values.

Table 4 provides the values of expanded uncertainty, in HRC units, for the INMETRO´s PHSM as a function of the chosen conditions and hardness ranges. These values were calculated taking into account reference [1] and experimental sensitivity coefficients calculated as described before.

Table 4 - Values of the expanded uncertainties, in HRC units, for the INMETRO´s Primary Hardness Standard Machine, which were calculated from the chosen conditions and Rockwell C hardness ranges.

Condition/ HRC range	*20 - 25*	*40 - 45*	*60 - 65*
C1	***0.36***	***0.26***	***0.47***
C 2	***0.30***	***0.27***	***0.18***
C3	***0.30***	***0.27***	***0.18***
C4	***0.25***	***0.26***	***0.17***
C5	***0.25***	***0.26***	***0.17***

Figure 4 shows a comparison among the five testing conditions of the expanded uncertainties for the INMETRO´s PHSM, taking into account the three hardness ranges depicted (20 to 25 HRC, 40 to 45 HRC, and 60 to 65 HRC). This comparison allowed an assessment of the influence of the parameters of the process on the final value of the expanded uncertainty of the PHSM.

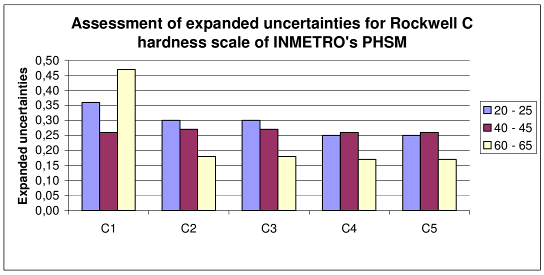

Figure 4 – Comparison of expanded uncertainties in HRC units applied to INMETRO´s Primary Hardness Standard Machine, as a function of the used conditions (and their inherent parameters values) and the hardness ranges.

From the analysis of Tables 1 and 4, along with the Figure 4 it was observed that on considering the experimental conditions, the calculated parameters had a positive behavior in terms of decreasing of the expanded uncertainty of PHSM for the Rockwell C hardness scale. It can be said the improvement of uncertainty knowledge lead to a better understanding of the characteristics of the INMETRO´s Primary Hardness Standard Machine.

The use of any experimental aspect (conditions C2, C3, C4 and C5) meant the use of a common character: all of them had four parameters calculated experimentally (internal angle of the indenter, indenter radius, indentation depth and indentation velocity). Condition 2 showed a moderate reduction of uncertainty in the range 20 to 25 HRC and a marked reduction of uncertainty for the range from 60 to 65 HRC. However, there is no significant change in the values of uncertainty in the range 40 to 45 HRC, which seems not to be affected by the used procedure, e.g. no matter there was a reference or an experimental condition. Regarding C2, a similar behavior could be observed for the condition 3, although the latter used experimental data for the parameter called “time of initial force application”. When analyzing the behavior of conditions 4 and 5, it could be realized that there was an equal expanded uncertainty for both conditions in all three hardness ranges analyzed. However, it should be emphasized that the sensitivity coefficient related to the independent variable “time of additional force application” was responsible in conditions C4 and C5 (due to their inherent experimental aspect) for a significant reduction in terms of hardness uncertainty in the range 20 to 25 HRC, compared to conditions 2 and 3 – and a slight reduction in the uncertainty for the low and high hardness range levels. Furthermore, through analysis of the precedent results it could be concluded the time of initial force application hasn’t influenced the reduction of expanded uncertainty of the INMETRO´s PHSM when dealing with Rockwell C hardness scale testing.

Although conditions 4 and 5 provided the same values for the relevant uncertainties in the three hardness ranges studied, C5 instead of C4 should be used since it is a consequence of six experimental values whereas C4 represents only five experimentally determined values. The discussion in this paragraph means C5 is a better representation of the characteristic and intrinsic behaviour of the INMETRO´s Primary Hardness Standard Machine.

By analyzing the reported results so far, among all possible candidates for becoming the INMETRO´s PHSM´s BMC for Rockwell hardness scale, condition C5 would be the best one due to the technical reasons exposed before. In this case, the best measurement capability to be considered for the INMETRO´s PHSM would change from the actual value 0.3 HRC to a new one 0.17 HRC (taking into account two significant digits) or 0.2 HRC (one significant digit), e.g. a reduction of 33.33%.

This fact proves extracting as many as possible data from actual characteristics of INMETRO´s PHSM was a suitable decision towards the improvement of the mentioned BMC. Further studies will be conducted in order to determine the influence of the experimental parameters "intitial force" and "additional force". This way an overall calculation of the sensitivity coefficients will be made and the best measurement capability for Rockwell hardness scale determined in this work can be improved in the future.

4. CONCLUSIONS

a) This study evaluated the variation in the values of the expanded uncertainties in Rockwell C hardness in terms of reference and experimental values of the uncertainty contributions. Thus, it was possible to show an upgrade in quality of results when studying the parameters considering their actual values, obtained experimentally in this work.
b) Experiments in the INMETRO´s PHSM can be summarized:
- experimental data for the uncertainty contributions "internal angle of the indenter", "indenter radius", "indentation depth" and "indentation velocity" resulted in a decrease of 0.36 to 0.30 HRC (reduction of 16.67%) in the expanded uncertainty of the range 20 to 25 HRC, and a sharp reduction in the expanded uncertainty from 0.47 to 0.18 HRC in the range 60 to 65 HRC (reduction of 61.70%);
- when using experimental values for the uncertainty contribution of the "time of additional force application" it was noticed a decrease of 0.30 to 0.25 HRC in the range 20 to 25 HRC (reduction of 16.67%), and a tiny reduction from 0.18 to 0.17 HRC in the range 60 to 65 HRC (reduction of 5.55%);
- use of "time of initial force application" no matter obtained experimentally or from the EURAMET hardness guide's reference value had no influence at all in the BMC of the INMETRO's Primary Hardness Standard Machine;
- hardness range 40 to 45 HRC had no sensitivity to any experimental or reference uncertainty contribution values.

c) As a function of this study INMETRO's Primary Hardness Standard Machine exhibited a value of 0.17 HRC (taking into account two significant digits) or 0.2 HRC (one significant digit) in its best measurement capability for Rockwell C hardness scale.

ACKNOWLEDGMENTS

The authors acknowledge the financial support granted from FINEP and CNPq / Prometro Projects for the development of this work.

REFERENCES

[1] Euramet Calibration Guide cg-16/v.01 "Guidelines on the Estimation of Uncertainty in Hardness Measurements", European Association of National Metrology Institutes, July 2007.
[2] ISO GUM 95, Guide to the Expression of Uncertainty in Measurement, 3rd edition in Brazilian Portuguese, INMETRO National Institute of Metrology, Standardization and Industrial Quality and ABNT Brazilian Association of Technical Standards, Rio de Janeiro, 2003.
[3] ISO Standard 6508-2:2005 "Metallic Materials - Rockwell hardness test - Part 2: Verification and calibration of testing machines (scales A, B, C, D, E, F, G, H, K, N, T)".
[4] ISO Standard 6508-3:2005 "Metallic Materials - Rockwell hardness test - Part 3: Calibration of reference blocks (scales A, B, C, D, E, F, G, H, K, N, T)".
[5] ISO Standard 6508-1:2005 "Metallic Materials – Rockwell hardness test - Part 1: Test method (scales A, B, C, D, E, F, G, H, K, N, T)".