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PRACTICAL IMPLICATIONS TO THE IMPROVEMENT OF HARDNESS SCALES DEFINITIONS

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Abstract – Recently, in the framework of the Working Group on Hardness (WGH) of the Consultative Committee for Mass and Related Quantities (CCM) of the Comité International des Poids et Mesures (CIPM), the opportunity to improve the definitions of the hardness scales has been discussed.

In this paper is investigated, from the theoretical point of view, the benefits in terms of decreasing of uncertainty subsequently to the approval of new definitions. The analysis will be done on the most important Rockwell, Vickers and Brinell hardness scales, but it will be possible to extend the benefits easily to all other scales.

Keywords: hardness, definition, uncertainty

1. INTRODUCTION

National Metrology Institutes (NMIs) have demonstrated their interest to the improvement of the definitions in order to fulfil to the requirements of an improvement of the level of uncertainty of hardness measurements demanded from the measuring activities of test, calibration and industrial laboratories.

As it is well known, due to the conventionality of the method, present definitions declared in the relative standards, have been adopted by NMIs even if they have not been directly studied and approved by them; in fact, standards are essentially addressed to test and calibration laboratories and they do not take into consideration (if not in indirect way) formal and substantial demands of the highest levels of the traceability chain that are deputed to the realization of hardness scales.

The fundamental question is following: are new proposed definitions (that we hope will be adopted in a short time) in the position to improve the uncertainty of the realization of the hardness scales?

The answer to this question is possible analysing the matter from two points of view: theoretical and experimental. The experimental one, has been investigated, for example, during last international comparisons, where have been proposed different protocols for the comparison in order to see the practical repercussions of different specifications. From the theoretical point of view, some analysis have been carried out, for example, in the guideline for the calculation of the uncertainty in hardness measurements issued by EA [1], in which the calculation of the uncertainty of the definition is reported, as well the level of uncertainty reached at the state of the art of primary hardness standard machines.

More investigations are necessary to validate the efforts of the CCM-WGH to have metrological definitions to be adopted at the level of NMIs.

Following, a theoretical analysis of the reduction of the uncertainty on the main hardness scales on metallic materials is done following the ISO GUM [2] recommendations

2. TRACEABILITY CHAIN

The dissemination of hardness scales (fig. 1) begin from hardness scale definitions where the measurement method associated with the relevant tolerances of the involved quantities is described. The definitions are used to design and realize hardness reference machines that materialise hardness scale definitions. Distinction should be made between primary standard machines, which constitute the best possible realisation of the hardness scale definitions, and calibration machines, used for the production of hardness reference blocks. The machines are used to calibrate hardness reference blocks. Again, one may distinguish between primary hardness reference blocks, calibrated by primary hardness standard machines and used when the highest accuracy is required, and hardness reference blocks intended mainly for the verification and calibration of industrial hardness testing machines.

The uncertainty of the scale definitions, produced by the tolerances adopted and by the lack of definition of some influence factors is the first step in the uncertainty budget [3, 4]. The second is the uncertainty of the nominal materialisation of the scale definition, produced by the uncertainty of the factors defined by the scale definitions and the third is the uncertainty of the effective materialisation of the scale definition, produced by all the other the factors not defined by the scale definitions.

With the result of this three-step uncertainty calculation, is possible to calculate the uncertainty of the primary hardness reference blocks calibration, from which the uncertainty of the other levels of the metrological chain is derived.

Is now clear that a reduction of the uncertainty at the first steps has direct practical implications in the reduction of the uncertainty in all other subsequent levels.

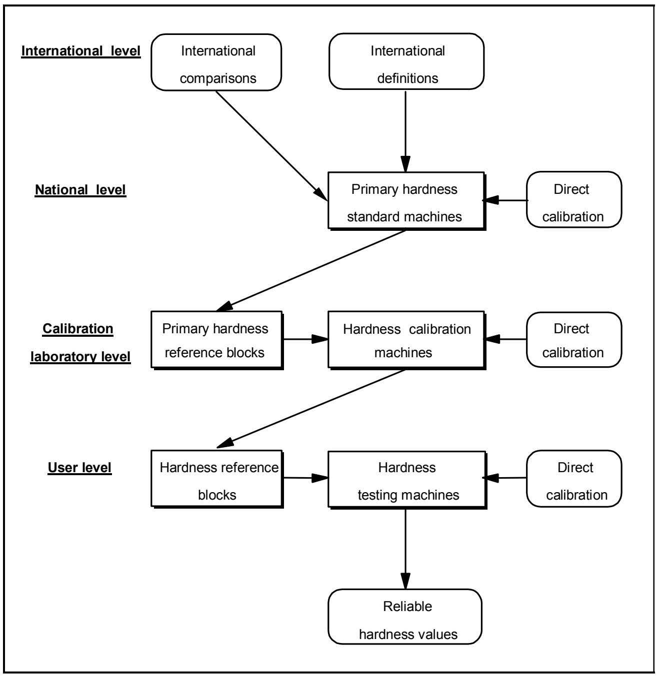

Fig. 1. four-level structure of the metrological chain necessary to define and disseminate hardness scales.

3. ANALYSIS

2.1. Present situation

The analysis begins considering the present situation, where, at international level, the used definitions are those indicated in the ISO standards, 650x series (part 3) [5, 6, 7].

Considering the tolerances of the influence factors as defined in the standards and associating some values (derived from the practical experience in the materialization of the hardness scales made in several NMIs) to the undefined influence factors, the uncertainty of the definition, calculated following the EA guide [1], for some of the main important Brinell, Vickers and Rockwell scales are reported in tables I, II, III.

The same type of calculation is used to estimate the uncertainty at the second step (materialization of the hardness scales through the primary hardness standard machines). In this case the best realization for each single factor should be included, but the problem arise when in the definition is not indicated a reference value, but only a tolerance. In fact, when any NMI for the realization of the hardness scales can choose influence factors inside a more or less large band of values indifferently, the results are surely different and the uncertainty must contain this possible difference.

Therefore, when we calculate the uncertainty of the primary hardness standard machines, only the contributions due to influence factor having a reference value can be estimated with the calibration of the machine (and evaluated as Type A factor): for the other factors, the total tolerance must be considered and evaluated as Type B factor.

TABLE I. Uncertainty due to the definition (ISO standards, series 6506, part 3) for some Brinell scales.

Brinell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Test force	F	N	**294.20**	**0.1%**	2.9E-01	2.9E-02	2.3E+00	1.5E-01
Indentation diameter	d	mm	**0.240**	**0.0005**	5.0E-04	8.3E-08	-1.4E+03	1.5E-01
Ball diameter	D	mm	**1**	**0.001**	1.0E-03	3.3E-07	-2.0E+01	1.3E-04
Numerical Aperture	NA			**1%**	6.5E+00	1.4E+01	1.0E+00	1.4E+01
Test force application time	t_1	s	**7**	**1**	1.0E+00	3.3E-01	2.1E-01	1.4E-02
Test force duration time	t_2	s	**12.5**	**2.5**	2.5E+00	2.1E+00	-6.0E-02	7.6E-03
Total								1.5E+01
Combined standard uncertainty $u(H)$								3.8E+00
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$						**7.6 HBW1/30**		
Relative Expanded standard uncertainty $U_{rel}(H)$						**1.2 %**		
Hardness	**653.5 HBW1/30**							

Brinell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Test force	F	N	**1838.7**	**0.1%**	1.8E+00	1.1E+00	3.6E-01	1.5E-01
Indentation diameter	d	mm	**0.600**	**0.0005**	5.0E-04	8.3E-08	-5.4E+02	2.4E-02
Ball diameter	D	mm	**2.5**	**0.001**	1.0E-03	3.3E-07	-8.0E+00	2.1E-05
Numerical Aperture	NA			**1%**	6.5E+00	1.4E+01	1.0E+00	1.4E+01
Test force application time	t_1	s	**7**	**1**	1.0E+00	3.3E-01	2.1E-01	1.4E-02
Test force duration time	t_2	s	**12.5**	**2.5**	2.5E+00	2.1E+00	-6.0E-02	7.6E-03
Total								1.4E+01
Combined standard uncertainty $u(H)$								3.8E+00
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$						**7.6 HBW2,5/187,5**		
Relative Expanded standard uncertainty $U_{rel}(H)$						**1.2 %**		
Hardness	**653.5 HBW2,5/187,5**							

Brinell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Test force	F	N	**7355.0**	**0.1%**	7.4E+00	1.8E+01	9.1E-02	1.5E-01
Indentation diameter	d	mm	**1.200**	**0.001**	1.0E-03	3.3E-07	-2.7E+02	2.4E-02
Ball diameter	D	mm	**5**	**0.002**	2.0E-03	1.3E-06	-4.0E+00	2.1E-05
Numerical Aperture	NA			**1%**	6.5E+00	1.4E+01	1.0E+00	1.4E+01
Test force application time	t_1	s	**7**	**1**	1.0E+00	3.3E-01	2.1E-01	1.4E-02
Test force duration time	t_2	s	**12.5**	**2.5**	2.5E+00	2.1E+00	-6.0E-02	7.6E-03
Total								1.4E+01
Combined standard uncertainty $u(H)$								3.8E+00
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$						**7.6 HBW5/750**		
Relative Expanded standard uncertainty $U_{rel}(H)$						**1.2 %**		
Hardness	**653.5 HBW5/750**							

Brinell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Test force	F	N	**29420.0**	**0.1%**	2.9E+01	2.9E+02	2.1E-02	1.3E-01
Indentation diameter	d	mm	**2.500**	**0.002**	2.0E-03	1.3E-06	-1.2E+02	2.1E-02
Ball diameter	D	mm	**10**	**0.003**	3.0E-03	3.0E-06	-2.0E+00	1.2E-05
Numerical Aperture	NA			**1%**	6.0E+00	1.2E+01	1.0E+00	1.2E+01
Uniformity (max error of d)		%		**1%**	1.1E-02	4.2E-05	-1.2E+02	6.5E-01
Test force application time	t_1	s	**7**	**1**	1.0E+00	3.3E-01	2.0E-01	1.3E-02
Test force duration time	t_2	s	**12.5**	**2.5**	2.5E+00	2.1E+00	-6.8E-02	9.6E-03
Total								1.3E+01
Combined standard uncertainty $u(H)$								3.6E+00
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$						**7.2 HBW10/3000**		
Relative Expanded standard uncertainty $U_{rel}(H)$						**1.2 %**		
Hardness	**601.5 HBW10/3000**							

TABLE II. Uncertainty due to the definition (ISO standards, series 6507, part 3) for some Vickers scales.

Vickers - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Test force	F	N	**1.96**	**0.1%**	2.0E-03	1.3E-06	4.4E+02	2.5E-01
Indentation diagonal length	d	mm	**0.021**	**0.0002**	2.0E-04	1.3E-08	-8.3E+04	9.2E+01
Numerical Aperture	NA			**1%**	8.6E+00	2.5E+01	1.0E+00	2.5E+01
Test force application time	t_1	s	**5**	**5**	5.0E+00	8.3E+00	-6.4E-01	3.4E+00
Test force duration time	t_2	s	**14**	**1**	1.0E+00	3.3E-01	2.2E-01	1.5E-02
Approach velocity	v	mm/s	**0.125**	**0.075**	7.5E-02	1.9E-03	6.4E-01	7.7E-04
Plane angle	α	°	**136**	**0.1**	1.0E-01	3.3E-03	1.7E+02	1.0E+02
Tip radius	r	mm	**0**	**0.0005**	5.0E-04	8.3E-08	-4.8E+04	1.9E+02
Length of line of junction	c	mm	**0**	**0.0005**	5.0E-04	8.3E-08	5.8E+04	2.8E+02
Total								7.0E+02
Combined standard uncertainty $u(H)$								2.6E+01
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$						**52.8 HV0,2**		
Relative Expanded standard uncertainty $U_{rel}(H)$						**6.1 %**		
Hardness	**862.2 HV0,2**							

Vickers - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Test force	F	N	**9.81**	**0.1%**	9.8E-03	3.2E-05	8.9E+01	2.6E-01
Indentation diagonal length	d	mm	**0.046**	**0.5%**	2.3E-04	1.8E-08	-3.8E+04	2.6E+01
Numerical Aperture	NA			**1%**	8.8E+00	2.6E+01	1.0E+00	2.6E+01
Test force application time	t_1	s	**5**	**5**	5.0E+00	8.3E+00	-6.5E-01	3.5E+00
Test force duration time	t_2	s	**14**	**1**	1.0E+00	3.3E-01	2.2E-01	1.6E-02
Approach velocity	v	mm/s	**0.125**	**0.075**	7.5E-02	1.9E-03	6.5E-01	7.9E-04
Plane angle	α	°	**136**	**0.1**	1.0E-01	3.3E-03	1.8E+02	1.0E+02
Tip radius	r	mm	**0**	**0.0005**	5.0E-04	8.3E-08	-2.1E+04	3.8E+01
Length of line of junction	c	mm	**0**	**0.0005**	5.0E-04	8.3E-08	2.7E+04	5.9E+01
Total								2.6E+02
Combined standard uncertainty $u(H)$								1.6E+01
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$						**32.0 HV1**		
Relative Expanded standard uncertainty $U_{rel}(H)$						**3.7 %**		
Hardness	**875.3 HV1**							

Vickers - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Test force	F	N	**294.20**	**0.1%**	2.9E-01	2.9E-02	2.8E+00	2.2E-01
Indentation diagonal length	d	mm	**0.260**	**0.001**	1.0E-03	3.3E-07	-6.3E+03	1.3E+01
Numerical Aperture	NA			**1%**	8.2E+00	2.2E+01	1.0E+00	2.2E+01
Test force application time	t_1	s	**7**	**1**	1.0E+00	3.3E-01	-5.9E-01	1.1E-01
Test force duration time	t_2	s	**14**	**1**	1.0E+00	3.3E-01	2.0E-01	1.4E-02
Approach velocity	v	mm/s	**0.525**	**0.475**	4.8E-01	7.5E-02	5.9E-01	2.6E-02
Plane angle	α	°	**136**	**0.1**	1.0E-01	3.3E-03	1.7E+02	9.2E+01
Tip radius	r	mm	**0**	**0.0005**	5.0E-04	8.3E-08	-3.5E+03	1.0E+00
Length of line of junction	c	mm	**0**	**0.001**	1.0E-03	3.3E-07	4.4E+03	6.5E+00
Total								1.4E+02
Combined standard uncertainty $u(H)$								1.2E+01
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$						**23.3 HV30**		
Relative Expanded standard uncertainty $U_{rel}(H)$						**2.8 %**		
Hardness	**820.8 HV30**							

TABLE III. Uncertainty due to the definition (ISO standards, series 6508, part 3) for Rockwell C scale.

Rockwell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Preliminary test force	F_0	N	**98.07**	**0.2%**	2.0E-01	1.3E-02	1.2E-01	1.8E-04
Total test force	F	N	**1471.0**	**0.1%**	1.5E+00	7.2E-01	-4.0E-02	1.2E-03
Indenter angle	α	°	**120**	**0.1**	1.0E-01	3.3E-03	1.3E+00	5.6E-03
Indenter radius	r	mm	**0.200**	**0.005**	5.0E-03	8.3E-06	1.5E+01	1.9E-03
Indentation depth	h	µm			2.0E-01	1.3E-02	5.0E-01	3.3E-03
Indentation velocity	v	µm/s	**30**	**10**	1.0E+01	3.3E+01	-2.0E-02	1.3E-02
Preliminary test force dwell time	t_0	s	**3**	**1**	1.0E+00	3.3E-01	1.0E-02	3.3E-05
Total test force dwell time	t	s	**4**	**2**	2.0E+00	1.3E+00	-7.0E-02	6.5E-03
Total								3.2E-02
Combined standard uncertainty $u(H)$								1.8E-01
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$								**0.36 HRC**
Hardness	**20.0 HRC**							

Rockwell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Preliminary test force	F_0	N	**98.07**	**0.2%**	2.0E-01	1.3E-02	7.0E-02	6.3E-05
Total test force	F	N	**1471.0**	**0.1%**	1.5E+00	7.2E-01	-3.0E-02	6.5E-04
Indenter angle	α	°	**120**	**0.1**	1.0E-01	3.3E-03	8.0E-01	2.1E-03
Indenter radius	r	µm	**0.200**	**0.005**	5.0E-03	8.3E-06	3.0E+01	7.5E-03
Indentation depth	h	µm			2.0E-01	1.3E-02	5.0E-01	3.3E-03
Indentation velocity	v	µm/s	**30**	**10**	1.0E+01	3.3E+01	0.0E+00	0.0E+00
Preliminary test force dwell time	t_0	s	**3**	**1**	1.0E+00	3.3E-01	5.0E-03	8.3E-06
Total test force dwell time	t	s	**4**	**2**	2.0E+00	1.3E+00	-4.0E-02	2.1E-03
Total								1.6E-02
Combined standard uncertainty $u(H)$								1.3E-01
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$								**0.25 HRC**
Hardness	**40.0 HRC**							

Rockwell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Preliminary test force	F_0	N	**98.07**	**0.2%**	2.0E-01	1.3E-02	5.0E-02	3.2E-05
Total test force	F	N	**1471.0**	**0.1%**	1.5E+00	7.2E-01	-2.0E-02	2.9E-04
Indenter angle	α	°	**120**	**0.1**	1.0E-01	3.3E-03	4.0E-01	5.3E-04
Indenter radius	r	µm	**0.200**	**0.005**	5.0E-03	8.3E-06	5.0E+01	2.1E-02
Indentation depth	h	µm			2.0E-01	1.3E-02	5.0E-01	3.3E-03
Indentation velocity	v	µm/s	**30**	**10**	1.0E+01	3.3E+01	3.0E-02	3.0E-02
Preliminary test force dwell time	t_0	s	**3**	**1**	1.0E+00	3.3E-01	4.0E-03	5.3E-06
Total test force dwell time	t	s	**4**	**2**	2.0E+00	1.3E+00	-3.0E-02	1.2E-03
Total								5.6E-02
Combined standard uncertainty $u(H)$								2.4E-01
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$								**0.47 HRC**
Hardness	**60.0 HRC**							

Results of this calculation for the IMGC-CNR (Italian NMI) primary hardness standard machines [8] are reported in tables IV, V, VI for the most important Brinell, Vickers and Rockwell scales respectively.

TABLE IV. Uncertainty of the best possible materialization of the ISO standards, series 6506, part 3 definition for some Brinell scales.

Brinell - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**294.20**	**0.01%**	2.9E-02	8.7E-04	2.3E+00	4.4E-03	30	6.6E-07
Indentation diameter	d	mm	**0.240**	**0.0005**	5.0E-04	2.5E-07	-1.4E+03	4.6E-01	9	2.3E-02
Ball diameter	D	mm	**1**	**0.001**	1.0E-03	1.0E-06	-2.0E+01	4.0E-04	30	5.4E-09
Numerical Aperture	NA			**1%**	6.5E+00	1.4E+01	1.0E+00	1.4E+01	100	2.0E+00
Test force application time	t_1	s	**7**	**1**	1.0E+00	3.3E-01	2.1E-01	1.4E-02	3	6.8E-05
Test force duration time	t_2	s	**12.5**	**2.5**	2.5E+00	2.1E+00	-6.0E-02	7.6E-03	3	1.9E-05
Total								1.5E+01		2.0E+00
Combined standard uncertainty $u(H)$								3.8E+00	ν_{eff}	105
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty $U(H)$								**7.6**	**HBW1/30**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**1.2**	**%**	
Hardness	**653.5 HBW1/30**									

Brinell - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**1838.7**	**0.01%**	1.8E-01	3.4E-02	3.6E-01	4.4E-03	30	6.6E-07
Indentation diameter	d	mm	**0.600**	**0.0005**	5.0E-04	2.5E-07	-5.4E+02	7.3E-02	9	6.0E-04
Ball diameter	D	mm	**2.5**	**0.001**	1.0E-03	1.0E-06	-8.0E+00	6.4E-05	30	1.4E-10
Numerical Aperture	NA			**1%**	6.5E+00	1.4E+01	1.0E+00	1.4E+01	100	2.0E+00
Test force application time	t_1	s	**7**	**1**	1.0E+00	3.3E-01	2.1E-01	1.4E-02	3	6.8E-05
Test force duration time	t_2	s	**12.5**	**2.5**	2.5E+00	2.1E+00	-6.0E-02	7.6E-03	3	1.9E-05
Total								1.4E+01		2.0E+00
Combined standard uncertainty $u(H)$								3.8E+00	ν_{eff}	101
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty $U(H)$								**7.5**	**HBW2,5/187,5**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**1.1**	**%**	
Hardness	**653.5 HBW2,5/187,5**									

Brinell - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**7355.0**	**0.01%**	7.4E-01	5.4E-01	9.1E-02	4.4E-03	30	6.6E-07
Indentation diameter	d	mm	**1.200**	**0.0010**	1.0E-03	1.0E-06	-2.7E+02	7.3E-02	9	6.0E-04
Ball diameter	D	mm	**5**	**0.002**	2.0E-03	4.0E-06	-4.0E+00	6.4E-05	30	1.4E-10
Numerical Aperture	NA			**1%**	6.5E+00	1.4E+01	1.0E+00	1.4E+01	100	2.0E+00
Test force application time	t_1	s	**7**	**1**	1.0E+00	3.3E-01	2.1E-01	1.4E-02	3	6.8E-05
Test force duration time	t_2	s	**12.5**	**2.5**	2.5E+00	2.1E+00	-6.0E-02	7.6E-03	3	1.9E-05
Total								1.4E+01		2.0E+00
Combined standard uncertainty $u(H)$								3.8E+00	ν_{eff}	101
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty $U(H)$								**7.5**	**HBW5/750**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**1.1**	**%**	
Hardness	**653.5 HBW5/750**									

Brinell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**29420.0**	**0.01%**	2.9E+00	8.7E+00	2.1E-02	3.8E-03	30	4.7E-07
Indentation diameter	d	mm	**2.500**	**0.001**	1.0E-03	1.0E-06	-1.2E+02	1.6E-02	9	2.7E-05
Ball diameter	D	mm	**10**	**0.003**	3.0E-03	9.0E-06	-2.0E+00	3.6E-05	30	4.4E-11
Numerical Aperture	NA			**1%**	6.0E+00	1.2E+01	1.0E+00	1.2E+01	100	1.5E+00
Test force application time	t_1	s	**7**	**1**	1.0E+00	3.3E-01	2.0E-01	1.3E-02	3	5.4E-05
Test force duration time	t_2	s	**12.5**	**2.5**	2.5E+00	2.1E+00	-6.8E-02	9.6E-03	3	3.1E-05
Total								1.2E+01		1.5E+00
Combined standard uncertainty $u(H)$								3.5E+00	ν_{eff}	100
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty $U(H)$								**6.9**	**HBW10/3000**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**1.1**	**%**	
Hardness	**601.5 HBW10/3000**									

As we can see in the tables, even if the IMGC-CNR machines try to have the best possible realization of the hardness scales (force applied by dead weights, indentations measured by laser interferometric system, cycle parameters controlled by a load cell, etc.), due to the lack of definition of some influence factor [9] that gives the main contribution to the uncertainty, the present limit of the uncertainty at this level is the definition itself.

TABLE V. Uncertainty of the best possible materialization of the ISO standards, series 6507, part 3 definition for some Vickers scales.

Vickers - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**1.96**	**0.01%**	2.0E-04	3.8E-08	4.4E+02	7.4E-03	30	1.8E-06
Indentation diagonal length	d	mm	**0.021**	**0.0002**	2.0E-04	4.0E-08	-8.3E+04	2.8E+02	9	8.5E+03
Numerical Aperture	NA			**1%**	4.3E+00	6.2E+00	1.0E+00	6.2E+00	100	3.8E-01
Test force application time	t_1	s	**5**	**5**	5.0E+00	8.3E+00	-6.4E-01	3.4E+00	3	3.9E+00
Test force duration time	t_2	s	**14**	**0.5**	5.0E-01	2.5E-01	2.2E-01	1.2E-02	3	4.8E-05
Approach velocity	v	mm/s	**0.125**	**0.075**	7.5E-02	1.9E-03	6.4E-01	7.7E-04	3	2.0E-07
Plane angle	α	°	**136**	**0.05**	5.0E-02	2.5E-03	1.7E+02	7.6E+01	30	1.9E+02
Tip radius	r	mm	**0**	**0.0002**	2.0E-04	4.0E-08	-4.7E+04	8.7E+01	9	8.4E+02
Length of line of junction	c	mm	**0**	**0.0002**	2.0E-04	4.0E-08	5.8E+04	1.4E+02	9	2.0E+03
Total								5.8E+02		1.2E+04
Combined standard uncertainty $u(H)$								2.4E+01	ν_{eff}	29
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty $U(H)$								**49.4**	**HV0,2**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**5.7**	**%**	
Hardness	**862.2 HV0,2**									

Vickers - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**9.81**	**0.01%**	9.8E-03	9.6E-05	8.9E+01	7.7E-01	30	2.0E-02
Indentation diagonal length	d	mm	**0.046**	**0.5%**	2.3E-04	5.3E-08	-3.8E+04	7.7E+01	9	6.5E+02
Numerical Aperture	NA			**1%**	8.8E+00	2.6E+01	1.0E+00	2.6E+01	100	6.5E+00
Test force application time	t_1	s	**5**	**5**	5.0E+00	8.3E+00	-6.5E-01	3.5E+00	3	4.1E+00
Test force duration time	t_2	s	**14**	**0.5**	5.0E-01	2.5E-01	2.2E-01	1.2E-02	3	5.1E-05
Approach velocity	v	mm/s	**0.125**	**0.075**	7.5E-02	1.9E-03	6.5E-01	7.9E-04	3	2.1E-07
Plane angle	α	°	**136**	**0.05**	5.0E-02	2.5E-03	1.8E+02	7.8E+01	30	2.0E+02
Tip radius	r	mm	**0**	**0.0002**	2.0E-04	4.0E-08	-2.1E+04	1.8E+01	9	3.5E+01
Length of line of junction	c	mm	**0**	**0.0002**	2.0E-04	4.0E-08	2.7E+04	2.8E+01	9	8.9E+01
Total								2.3E+02		9.9E+02
Combined standard uncertainty $u(H)$								1.5E+01	ν_{eff}	53
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty $U(H)$								**30.5**	**HV1**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**3.5**	**%**	
Hardness	**875.3 HV1**									

Vickers - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**294.20**	**0.01%**	2.9E-01	8.7E-02	2.8E+00	6.7E-01	30	1.5E-02
Indentation diagonal length	d	mm	**0.260**	**0.001**	1.0E-03	1.0E-06	-6.3E+03	4.0E+01	9	1.8E+02
Numerical Aperture	NA			**1%**	8.2E+00	2.2E+01	1.0E+00	2.2E+01	100	5.0E+00
Test force application time	t_1	s	**7**	**5**	5.0E+00	8.3E+00	-4.7E-01	1.9E+00	3	1.2E+00
Test force duration time	t_2	s	**14**	**0.5**	5.0E-01	2.5E-01	2.1E-01	1.1E-02	3	3.9E-05
Approach velocity	v	mm/s	**0.525**	**0.075**	7.5E-02	1.9E-03	4.7E-01	4.2E-04	3	5.9E-08
Plane angle	α	°	**136**	**0.05**	5.0E-02	2.5E-03	1.7E+02	6.9E+01	30	1.6E+02
Tip radius	r	mm	**0**	**0.0002**	2.0E-04	4.0E-08	-3.5E+03	4.8E-01	9	2.6E-02
Length of line of junction	c	mm	**0**	**0.0002**	2.0E-04	4.0E-08	4.4E+03	7.8E-01	9	6.8E-02
Total								1.3E+02		3.4E+02
Combined standard uncertainty $u(H)$								1.2E+01	ν_{eff}	53
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty $U(H)$								**23.3**	**HV30**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**2.8**	**%**	
Hardness	**820.8 HV30**									

TABLE VI. Uncertainty of the best possible materialization of the ISO standards, series 6508, part 3 definition for Rockwell C scale.

Rockwell - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Preliminary test force	F_0	N	**98.07**	**0.02%**	2.0E-02	3.8E-04	1.2E-01	5.5E-06	30	1.0E-12
Total test force	F	N	**1471.0**	**0.01%**	1.5E-01	2.2E-02	-4.0E-02	3.5E-05	30	4.0E-11
Indenter angle	α	°	**120**	**0.05**	5.0E-02	2.5E-03	1.3E+00	4.2E-03	15	1.2E-06
Indenter radius	r	mm	**0.200**	**0.001**	1.0E-03	1.0E-06	1.5E+01	2.3E-04	15	3.4E-09
Indentation depth	h	µm		**0.02**	2.0E-02	4.0E-04	5.0E-01	1.0E-04	30	3.3E-10
Indentation velocity	v	µm/s	**30**	**10**	1.0E+01	3.3E+01	-2.0E-02	1.3E-02	100	1.8E-06
Preliminary test force dwell time	t_0	s	**3**	**1.5**	1.5E+00	2.3E+00	1.0E-02	2.3E-04	100	5.1E-10
Total test force dwell time	t	s	**4**	**0.5**	5.0E-01	2.5E-01	-7.0E-02	1.2E-03	9	1.7E-07
Total								1.9E-02		3.1E-06
Combined standard uncertainty $u(H)$								1.4E-01	ν_{eff}	119
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty $U(H)$								**0.28**	**HRC**	
Hardness	**20.0 HRC**									

Rockwell - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Preliminary test force	F_0	N	**98.07**	**0.02%**	2.0E-02	3.8E-04	7.0E-02	1.9E-06	30	1.2E-13
Total test force	F	N	**1471.0**	**0.01%**	1.5E-01	2.2E-02	-3.0E-02	1.9E-05	30	1.3E-11
Indenter angle	α	°	**120**	**0.05**	5.0E-02	2.5E-03	8.0E-01	1.6E-03	15	1.7E-07
Indenter radius	r	µm	**0.200**	**0.001**	1.0E-03	1.0E-06	3.0E+01	9.0E-04	15	5.4E-08
Indentation depth	h	µm		**0.02**	2.0E-02	4.0E-04	5.0E-01	1.0E-04	30	3.3E-10
Indentation velocity	v	µm/s	**30**	**10**	1.0E+01	3.3E+01	0.0E+00	0.0E+00	100	0.0E+00
Preliminary test force dwell time	t_0	s	**3**	**1.5**	1.5E+00	2.3E+00	5.0E-03	5.6E-05	100	3.2E-11
Total test force dwell time	t	s	**4**	**0.5**	5.0E-01	2.5E-01	-4.0E-02	4.0E-04	9	1.8E-08
Total								3.1E-03		2.4E-07
Combined standard uncertainty $u(H)$								5.5E-02	ν_{eff}	39
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty $U(H)$								**0.11**	**HRC**	
Hardness	**40.0 HRC**									

Rockwell - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Preliminary test force	F_0	N	**98.07**	**0.02%**	2.0E-02	3.8E-04	5.0E-02	9.6E-07	30	3.1E-14
Total test force	F	N	**1471.0**	**0.01%**	1.5E-01	2.2E-02	-2.0E-02	8.7E-06	30	2.5E-12
Indenter angle	α	°	**120**	**0.05**	5.0E-02	2.5E-03	4.0E-01	4.0E-04	15	1.1E-08
Indenter radius	r	µm	**0.200**	**0.001**	1.0E-03	1.0E-06	5.0E+01	2.5E-03	15	4.2E-07
Indentation depth	h	µm		**0.02**	2.0E-02	4.0E-04	5.0E-01	1.0E-04	30	3.3E-10
Indentation velocity	v	µm/s	**30**	**10**	1.0E+01	3.3E+01	3.0E-02	3.0E-02	100	9.0E-06
Preliminary test force dwell time	t_0	s	**3**	**1.5**	1.5E+00	2.3E+00	4.0E-03	3.6E-05	100	1.3E-11
Total test force dwell time	t	s	**4**	**0.5**	5.0E-01	2.5E-01	-3.0E-02	2.3E-04	9	5.6E-09
Total								3.3E-02		9.4E-06
Combined standard uncertainty $u(H)$								1.8E-01	ν_{eff}	117
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty $U(H)$								**0.36**	**HRC**	
Hardness	**60.0 HRC**									

2.2. Possible improvements

At the level of the CCM-WGH, it is been proposed is to have definitions with the best possible description of the indentation testing cycle and with reference values for each influence parameter involved in the hardness tests [10].

Working in this direction, it is possible to eliminate totally the uncertainty of the definition, beginning the calculation of the uncertainty directly from the second step (materialization of the hardness scales), even if some problems to be solved remain.

In fact, some influence factors cannot be easily defined, like the Numerical Aperture of lenses and illumination systems of the Vickers and Brinell optical measuring systems.

It is known and it has been recently confirmed in the last Vickers Key Comparison of the CIPM, that NA has influence in the size of the image of the Vickers and Brinell indentations. The quantification of this effect depends by the size of the indentation and by the material of the hardness blocks; then is not easy to calculate a correlation function for this effect but we can estimate this effect as ±1% of the dimension of the indentation (from 0,07 to 0,4 of NA).

A possibility is trying to define a restricted range of possible NA depending by the size of the indentation to be measured: in fact, NA is normally correlated to the magnification of the lens. In this way we can reduce this effect of about two times, therefore ±0,5%.

To calculate benefits deriving from this formulation, results for the IMGC-CNR primary hardness standard machines are presented in tables VII, VIII, IX.

TABLE VII. Uncertainty of the best possible materialization of the CCM -WGH possible definition for some Brinell scales.

Brinell - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**294.20**	**0.01%**	2.9E-02	8.7E-04	2.3E+00	4.4E-03	30	6.6E-07
Indentation diameter	d	mm	**0.240**	**0.0005**	5.0E-04	2.5E-07	-1.4E+03	4.6E-01	9	2.3E-02
Ball diameter	D	mm	**1**	**0.001**	1.0E-03	1.0E-06	-2.0E+01	4.0E-04	30	5.4E-09
Numerical Aperture	NA			**0.5%**	3.3E+00	3.6E+00	1.0E+00	3.6E+00	9	1.4E+00
Test force application time	t_1	s	**7**	**0.5**	5.0E-01	2.5E-01	2.1E-01	1.1E-02	3	3.8E-05
Test force duration time	t_2	s	**12.5**	**0.5**	5.0E-01	2.5E-01	-6.0E-02	9.1E-04	3	2.8E-07
Total								4.0E+00		1.4E+00
Combined standard uncertainty *u (H)*								2.0E+00	ν_{eff}	11
Confidence level								95%		
Coverage factor								2.2		
Expanded standard uncertainty *U (H)*								**4.4**	**HBW1/30**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**0.7**	**%**	
Hardness	**653.5 HBW1/30**									

Brinell - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**1838.7**	**0.01%**	1.8E-01	3.4E-02	3.6E-01	4.4E-03	30	6.6E-07
Indentation diameter	d	mm	**0.600**	**0.0005**	5.0E-04	2.5E-07	-5.4E+02	7.3E-02	9	6.0E-04
Ball diameter	D	mm	**2.5**	**0.001**	1.0E-03	1.0E-06	-8.0E+00	6.4E-05	30	1.4E-10
Numerical Aperture	NA			**0.5%**	3.3E+00	3.6E+00	1.0E+00	3.6E+00	9	1.4E+00
Test force application time	t_1	s	**7**	**0.5**	5.0E-01	2.5E-01	2.1E-01	1.1E-02	3	3.8E-05
Test force duration time	t_2	s	**12.5**	**0.5**	5.0E-01	2.5E-01	-6.0E-02	9.1E-04	3	2.8E-07
Total								3.6E+00		1.4E+00
Combined standard uncertainty *u (H)*								1.9E+00	ν_{eff}	9
Confidence level								95%		
Coverage factor								2.3		
Expanded standard uncertainty *U (H)*								**4.3**	**HBW2,5/187,5**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**0.7**	**%**	
Hardness	**653.5 HBW2,5/187,5**									

Brinell - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**7355.0**	**0.01%**	7.4E-01	5.4E-01	9.1E-02	4.4E-03	30	6.6E-07
Indentation diameter	d	mm	**1.200**	**0.0010**	1.0E-03	1.0E-06	-2.7E+02	7.3E-02	9	6.0E-04
Ball diameter	D	mm	**5**	**0.002**	2.0E-03	4.0E-06	-4.0E+00	6.4E-05	30	1.4E-10
Numerical Aperture	NA			**0.5%**	3.3E+00	3.6E+00	1.0E+00	3.6E+00	9	1.4E+00
Test force application time	t_1	s	**7**	**0.5**	5.0E-01	2.5E-01	2.1E-01	1.1E-02	3	3.8E-05
Test force duration time	t_2	s	**12.5**	**0.5**	5.0E-01	2.5E-01	-6.0E-02	9.1E-04	3	2.8E-07
Total								3.6E+00		1.4E+00
Combined standard uncertainty *u (H)*								1.9E+00	ν_{eff}	9
Confidence level								95%		
Coverage factor								2.3		
Expanded standard uncertainty *U (H)*								**4.3**	**HBW5/750**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**0.7**	**%**	
Hardness	**653.5 HBW5/750**									

Brinell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**29420.0**	**0.01%**	2.9E+00	8.7E+00	2.1E-02	3.8E-03	30	4.7E-07
Indentation diameter	d	mm	**2.500**	**0.001**	1.0E-03	1.0E-06	-1.2E+02	1.6E-02	9	2.7E-05
Ball diameter	D	mm	**10**	**0.003**	3.0E-03	9.0E-06	-2.0E+00	3.6E-05	30	4.4E-11
Numerical Aperture	NA			**0.5%**	3.0E+00	3.0E+00	1.0E+00	3.0E+00	9	1.0E+00
Test force application time	t_1	s	**7**	**0.5**	5.0E-01	2.5E-01	2.0E-01	9.6E-03	3	3.0E-05
Test force duration time	t_2	s	**12.5**	**0.5**	5.0E-01	2.5E-01	-6.8E-02	1.2E-03	3	4.4E-07
Total								3.0E+00		1.0E+00
Combined standard uncertainty *u (H)*								1.7E+00	ν_{eff}	9
Confidence level								95%		
Coverage factor								2.3		
Expanded standard uncertainty *U (H)*								**3.9**	**HBW10/3000**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**0.7**	**%**	
Hardness	**601.5 HBW10/3000**									

The ISO specifications remain useful and indispensable for the other levels of the metrological chain, in particular for the calibration level.

TABLE VIII. Uncertainty of the best possible materialization of the CCM -WGH possible definition for some Vickers scales.

Vickers - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**1.96**	**0.01%**	2.0E-04	3.8E-08	4.4E+02	7.4E-03	30	1.8E-06
Indentation diagonal length	d	mm	**0.021**	**0.0002**	2.0E-04	4.0E-08	-8.3E+04	2.8E+02	9	8.5E+03
Numerical Aperture	NA			**0.5%**	4.3E+00	6.2E+00	1.0E+00	6.2E+00	9	4.3E+00
Test force application time	t_1	s	**5**	**0.5**	5.0E-01	2.5E-01	-8.8E-01	1.9E-01	3	1.2E-02
Test force duration time	t_2	s	**14**	**0.5**	5.0E-01	2.5E-01	2.2E-01	1.2E-02	3	4.8E-05
Approach velocity	v	mm/s	**0.125**	**0.01**	1.0E-02	1.0E-04	8.8E-01	7.7E-05	3	2.0E-09
Plane angle	α	°	**136**	**0.05**	5.0E-02	2.5E-03	1.7E+02	7.6E+01	30	1.9E+02
Tip radius	r	mm	**0**	**0.0002**	2.0E-04	4.0E-08	-4.7E+04	8.7E+01	9	8.4E+02
Length of line of junction	c	mm	**0**	**0.0002**	2.0E-04	4.0E-08	5.8E+04	1.4E+02	9	2.0E+03
Total								5.8E+02		1.2E+04
Combined standard uncertainty *u (H)*								2.4E+01	ν_{eff}	29
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty *U (H)*								**49.3**	**HV0,2**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**5.7**	**%**	
Hardness	**862.2 HV0,2**									

Vickers - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**9.81**	**0.01%**	9.8E-03	9.6E-05	8.9E+01	7.7E-01	30	2.0E-02
Indentation diagonal length	d	mm	**0.046**	**0.5%**	2.3E-04	5.3E-08	-3.8E+04	7.7E+01	9	6.5E+02
Numerical Aperture	NA			**0.5%**	4.4E+00	6.4E+00	1.0E+00	6.4E+00	9	4.5E+00
Test force application time	t_1	s	**5**	**0.5**	5.0E-01	2.5E-01	-8.9E-01	2.0E-01	3	1.3E-02
Test force duration time	t_2	s	**14**	**0.5**	5.0E-01	2.5E-01	2.2E-01	1.2E-02	3	5.1E-05
Approach velocity	v	mm/s	**0.125**	**0.01**	1.0E-02	1.0E-04	8.9E-01	8.0E-05	3	2.1E-09
Plane angle	α	°	**136**	**0.05**	5.0E-02	2.5E-03	1.8E+02	7.8E+01	30	2.0E+02
Tip radius	r	mm	**0**	**0.0002**	2.0E-04	4.0E-08	-2.1E+04	1.8E+01	9	3.5E+01
Length of line of junction	c	mm	**0**	**0.0002**	2.0E-04	4.0E-08	2.7E+04	2.8E+01	9	8.9E+01
Total								2.1E+02		9.8E+02
Combined standard uncertainty *u (H)*								1.4E+01	ν_{eff}	44
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty *U (H)*								**29.1**	**HV1**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**3.3**	**%**	
Hardness	**875.3 HV1**									

Vickers - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Test force	F	N	**294.20**	**0.01%**	2.9E-01	8.7E-02	2.8E+00	6.7E-01	30	1.5E-02
Indentation diagonal length	d	mm	**0.260**	**0.001**	1.0E-03	1.0E-06	-6.3E+03	4.0E+01	9	1.8E+02
Numerical Aperture	NA			**0.5%**	4.1E+00	5.6E+00	1.0E+00	5.6E+00	9	3.5E+00
Test force application time	t_1	s	**7**	**0.5**	5.0E-01	2.5E-01	-6.1E-01	9.2E-02	3	2.8E-03
Test force duration time	t_2	s	**14**	**0.5**	5.0E-01	2.5E-01	2.1E-01	1.1E-02	3	3.9E-05
Approach velocity	v	mm/s	**0.525**	**0.01**	1.0E-02	1.0E-04	6.1E-01	3.7E-05	3	4.5E-10
Plane angle	α	°	**136**	**0.05**	5.0E-02	2.5E-03	1.7E+02	6.9E+01	30	1.6E+02
Tip radius	r	mm	**0**	**0.0002**	2.0E-04	4.0E-08	-3.5E+03	4.8E-01	9	2.6E-02
Length of line of junction	c	mm	**0**	**0.0002**	2.0E-04	4.0E-08	4.4E+03	7.8E-01	9	6.8E-02
Total								1.2E+02		3.4E+02
Combined standard uncertainty *u (H)*								1.1E+01	ν_{eff}	40
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty *U (H)*								**21.8**	**HV30**	
Relative Expanded standard uncertainty $U_{rel}(H)$								**2.7**	**%**	
Hardness	**820.8 HV30**									

TABLE IX. Uncertainty of the best possible materialization of the CCM -WGH possible definition for Rockwell C scale.

Rockwell - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Preliminary test force	F_0	N	**98.07**	**0.02%**	2.0E-02	3.8E-04	1.2E-01	5.5E-06	30	1.0E-12
Total test force	F	N	**1471.0**	**0.01%**	1.5E-01	2.2E-02	-4.0E-02	3.5E-05	30	4.0E-11
Indenter angle	α	°	**120**	**0.05**	5.0E-02	2.5E-03	1.3E+00	4.2E-03	15	1.2E-06
Indenter radius	r	mm	**0.200**	**0.001**	1.0E-03	1.0E-06	1.5E+01	2.3E-04	15	3.4E-09
Indentation depth	h	µm		**0.02**	2.0E-02	4.0E-04	5.0E-01	1.0E-04	30	3.3E-10
Indentation velocity	v	µm/s	**30**	**3**	3.0E+00	9.0E+00	-2.0E-02	3.6E-03	3	4.3E-06
Preliminary test force dwell time	t_0	s	**3**	**0.5**	5.0E-01	2.5E-01	1.0E-02	2.5E-05	9	6.9E-11
Total test force dwell time	t	s	**4**	**0.5**	5.0E-01	2.5E-01	-7.0E-02	1.2E-03	9	1.7E-07
Total								9.4E-03		5.7E-06
Combined standard uncertainty *u (H)*								9.7E-02	ν_{eff}	15
Confidence level								95%		
Coverage factor								2.1		
Expanded standard uncertainty *U (H)*								**0.21**	**HRC**	
Hardness	**20.0 HRC**									

Rockwell - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Preliminary test force	F_0	N	**98.07**	**0.02%**	2.0E-02	3.8E-04	7.0E-02	1.9E-06	30	1.2E-13
Total test force	F	N	**1471.0**	**0.01%**	1.5E-01	2.2E-02	-3.0E-02	1.9E-05	30	1.3E-11
Indenter angle	α	°	**120**	**0.05**	5.0E-02	2.5E-03	8.0E-01	1.6E-03	15	1.7E-07
Indenter radius	r	µm	**0.200**	**0.001**	1.0E-03	1.0E-06	3.0E+01	9.0E-04	15	5.4E-08
Indentation depth	h	µm		**0.02**	2.0E-02	4.0E-04	5.0E-01	1.0E-04	30	3.3E-10
Indentation velocity	v	µm/s	**30**	**3**	3.0E+00	9.0E+00	0.0E+00	0.0E+00	3	0.0E+00
Preliminary test force dwell time	t_0	s	**3**	**0.5**	5.0E-01	2.5E-01	5.0E-03	6.3E-06	9	4.3E-12
Total test force dwell time	t	s	**4**	**0.5**	5.0E-01	2.5E-01	-4.0E-02	4.0E-04	9	1.8E-08
Total								3.0E-03		2.4E-07
Combined standard uncertainty *u (H)*								5.5E-02	ν_{eff}	37
Confidence level								95%		
Coverage factor								2.0		
Expanded standard uncertainty *U (H)*								**0.11**	**HRC**	
Hardness	**40.0 HRC**									

Rockwell - Influencing quantity X_i	Symbol	Unit	Value	State of the art	u_i, type A	$u^2(x_i)$	c_i	$u_i^2(H)$	ν_i	$u_i^4(H)/\nu_i$
Preliminary test force	F_0	N	**98.07**	**0.02%**	2.0E-02	3.8E-04	5.0E-02	9.6E-07	30	3.1E-14
Total test force	F	N	**1471.0**	**0.01%**	1.5E-01	2.2E-02	-2.0E-02	8.7E-06	30	2.5E-12
Indenter angle	α	°	**120**	**0.05**	5.0E-02	2.5E-03	4.0E-01	4.0E-04	15	1.1E-08
Indenter radius	r	µm	**0.200**	**0.001**	1.0E-03	1.0E-06	5.0E+01	2.5E-03	15	4.2E-07
Indentation depth	h	µm		**0.02**	2.0E-02	4.0E-04	5.0E-01	1.0E-04	30	3.3E-10
Indentation velocity	v	µm/s	**30**	**3**	3.0E+00	9.0E+00	3.0E-02	8.1E-03	3	2.2E-05
Preliminary test force dwell time	t_0	s	**3**	**0.5**	5.0E-01	2.5E-01	4.0E-03	4.0E-06	9	1.8E-12
Total test force dwell time	t	s	**4**	**0.5**	5.0E-01	2.5E-01	-3.0E-02	2.3E-04	9	5.6E-09
Total								1.1E-02		2.2E-05
Combined standard uncertainty *u (H)*								1.1E-01	ν_{eff}	5
Confidence level								95%		
Coverage factor								2.6		
Expanded standard uncertainty *U (H)*								**0.27**	**HRC**	
Hardness	**60.0 HRC**									

Moreover, analysing in tables I, II, III the column of contributions to the variance of each single factor, $u_i^2(H)$, one should noted that the weigh of some factors is much higher than others. The best condition consists to have the same amount of the contribution for all factors. For this reason a better optimisation of standard specifications can be achieved modifying the tolerances of the influence factors to have, for all factors, about the same influence; is quite simple to increase tolerance values in tables until this variations produce sensible effects in uncertainty results (table X, XI, XII).

TABLE X Uncertainty due to the proposed modified definition (ISO standards, series 6506, part 3) for some Brinell scales.

Brinell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Test force	F	N	**294.20**	**0.2%**	5.9E-01	1.2E-01	2.3E+00	5.9E-01
Indentation diameter	d	mm	**0.240**	**0.001**	1.0E-03	3.3E-07	-1.4E+03	6.1E-01
Ball diameter	D	mm	**1**	**0.05**	5.0E-02	8.3E-04	-2.0E+01	3.4E-01
Numerical Aperture	NA			**1%**	6.5E+00	1.4E+01	1.0E+00	1.4E+01
Test force application time	t_1	s	**7**	**5**	5.0E+00	8.3E+00	2.1E-01	3.6E-01
Test force duration time	t_2	s	**12.5**	**5**	5.0E+00	8.3E+00	-6.0E-02	3.0E-02
Total								1.6E+01
Combined standard uncertainty $u(H)$								4.0E+00
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$						**8.0 HBW1/30**		
Relative Expanded standard uncertainty $U_{rel}(H)$						**1.2 %**		
Hardness	**653.5 HBW1/30**							

Brinell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Test force	F	N	**1838.7**	**0.2%**	3.7E+00	4.5E+00	3.6E-01	5.9E-01
Indentation diameter	d	mm	**0.600**	**0.002**	2.0E-03	1.3E-06	-5.4E+02	3.9E-01
Ball diameter	D	mm	**2.5**	**0.1**	1.0E-01	3.3E-03	-8.0E+00	2.1E-01
Numerical Aperture	NA			**1%**	6.5E+00	1.4E+01	1.0E+00	1.4E+01
Test force application time	t_1	s	**7**	**5**	5.0E+00	8.3E+00	2.1E-01	3.6E-01
Test force duration time	t_2	s	**12.5**	**5**	5.0E+00	8.3E+00	-6.0E-02	3.0E-02
Total								1.6E+01
Combined standard uncertainty $u(H)$								4.0E+00
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$						**8.0 HBW2,5/187,5**		
Relative Expanded standard uncertainty $U_{rel}(H)$						**1.2 %**		
Hardness	**653.5 HBW2,5/187,5**							

Brinell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Test force	F	N	**7355.0**	**0.2%**	1.5E+01	7.2E+01	9.1E-02	5.9E-01
Indentation diameter	d	mm	**1.200**	**0.003**	3.0E-03	3.0E-06	-2.7E+02	2.2E-01
Ball diameter	D	mm	**5**	**0.2**	2.0E-01	1.3E-02	-4.0E+00	2.1E-01
Numerical Aperture	NA			**1%**	6.5E+00	1.4E+01	1.0E+00	1.4E+01
Test force application time	t_1	s	**7**	**5**	5.0E+00	8.3E+00	2.1E-01	3.6E-01
Test force duration time	t_2	s	**12.5**	**5**	5.0E+00	8.3E+00	-6.0E-02	3.0E-02
Total								1.6E+01
Combined standard uncertainty $u(H)$								4.0E+00
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$						**7.9 HBW5/750**		
Relative Expanded standard uncertainty $U_{rel}(H)$						**1.2 %**		
Hardness	**653.5 HBW5/750**							

Brinell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u^2(y_i)$
Test force	F	N	**29420.0**	**0.2%**	5.9E+01	1.2E+03	2.1E-02	5.0E-01
Indentation diameter	d	mm	**2.500**	**0.005**	5.0E-03	8.3E-06	-1.2E+02	1.3E-01
Ball diameter	D	mm	**10**	**0.5**	5.0E-01	8.3E-02	-2.0E+00	3.4E-01
Numerical Aperture	NA			**1%**	6.0E+00	1.2E+01	1.0E+00	1.2E+01
Uniformity (max error of d)		%		**1%**	1.1E-02	4.2E-05	-1.2E+02	6.5E-01
Test force application time	t_1	s	**7**	**5**	5.0E+00	8.3E+00	2.0E-01	3.2E-01
Test force duration time	t_2	s	**12.5**	**5**	5.0E+00	8.3E+00	-6.8E-02	3.8E-02
Total								1.4E+01
Combined standard uncertainty $u(H)$								3.7E+00
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$						**7.5 HBW10/3000**		
Relative Expanded standard uncertainty $U_{rel}(H)$						**1.2 %**		
Hardness	**601.5 HBW10/3000**							

TABLE XI Uncertainty due to the proposed modified definition (ISO standards, series 6506, part 3) for some Vickers scales.

Vickers - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Test force	F	N	**1.96**	**0.2%**	3.9E-03	5.1E-06	4.4E+02	9.9E-01
Indentation diagonal length	d	mm	**0.021**	**0.0002**	2.0E-04	1.3E-08	-8.3E+04	9.2E+01
Numerical Aperture	NA			**1%**	8.6E+00	2.5E+01	1.0E+00	2.5E+01
Test force application time	t_1	s	**5**	**5**	5.0E+00	8.3E+00	-6.4E-01	3.4E+00
Test force duration time	t_2	s	**14**	**10**	1.0E+01	3.3E+01	1.7E-01	9.4E-01
Approach velocity	v	mm/s	**0.125**	**2**	2.0E+00	1.3E+00	6.4E-01	5.5E-01
Plane angle	α	°	**136**	**0.1**	1.0E-01	3.3E-03	1.7E+02	1.0E+02
Tip radius	r	mm	**0**	**0.0005**	5.0E-04	8.3E-08	-4.8E+04	1.9E+02
Length of line of junction	c	mm	**0**	**0.0005**	5.0E-04	8.3E-08	5.8E+04	2.8E+02
Total								7.0E+02
Combined standard uncertainty $u(H)$								2.6E+01
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$							**52.9 HV0,2**	
Relative Expanded standard uncertainty $U_{rel}(H)$							**6.1 %**	
Hardness	**862.2 HV0,2**							

Vickers - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Test force	F	N	**9.81**	**0.2%**	9.8E-03	3.2E-05	8.9E+01	2.6E-01
Indentation diagonal length	d	mm	**0.046**	**0.5%**	2.3E-04	1.8E-08	-3.8E+04	2.6E+01
Numerical Aperture	NA			**1%**	8.8E+00	2.6E+01	1.0E+00	2.6E+01
Test force application time	t_1	s	**5**	**5**	5.0E+00	8.3E+00	-6.5E-01	3.5E+00
Test force duration time	t_2	s	**14**	**10**	1.0E+01	3.3E+01	1.7E-01	9.7E-01
Approach velocity	v	mm/s	**0.125**	**2**	2.0E+00	1.3E+00	6.5E-01	5.6E-01
Plane angle	α	°	**136**	**0.1**	1.0E-01	3.3E-03	1.8E+02	1.0E+02
Tip radius	r	mm	**0**	**0.0005**	5.0E-04	8.3E-08	-2.1E+04	3.8E+01
Length of line of junction	c	mm	**0**	**0.0005**	5.0E-04	8.3E-08	2.7E+04	5.9E+01
Total								2.6E+02
Combined standard uncertainty $u(H)$								1.6E+01
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$							**32.1 HV1**	
Relative Expanded standard uncertainty $U_{rel}(H)$							**3.7 %**	
Hardness	**875.3 HV1**							

Vickers - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Test force	F	N	**294.20**	**0.2%**	2.9E-01	2.9E-02	2.8E+00	2.2E-01
Indentation diagonal length	d	mm	**0.260**	**0.001**	1.0E-03	3.3E-07	-6.3E+03	1.3E+01
Numerical Aperture	NA			**1%**	8.2E+00	2.2E+01	1.0E+00	2.2E+01
Test force application time	t_1	s	**7**	**5**	5.0E+00	8.3E+00	-4.7E-01	1.9E+00
Test force duration time	t_2	s	**14**	**10**	1.0E+01	3.3E+01	1.6E-01	8.5E-01
Approach velocity	v	mm/s	**0.525**	**2**	2.0E+00	1.3E+00	4.7E-01	3.0E-01
Plane angle	α	°	**136**	**0.1**	1.0E-01	3.3E-03	1.7E+02	9.2E+01
Tip radius	r	mm	**0**	**0.0005**	5.0E-04	8.3E-08	-3.5E+03	1.0E+00
Length of line of junction	c	mm	**0**	**0.001**	1.0E-03	3.3E-07	4.4E+03	6.5E+00
Total								1.4E+02
Combined standard uncertainty $u(H)$								1.2E+01
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$							**23.5 HV30**	
Relative Expanded standard uncertainty $U_{rel}(H)$							**2.9 %**	
Hardness	**820.8 HV30**							

TABLE XII Uncertainty due to the proposed modified definition (ISO standards, series 6506, part 3) for Rockwell C scale.

Rockwell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Preliminary test force	F_0	N	**98.07**	**0.5%**	4.9E-01	8.0E-02	1.2E-01	1.2E-03
Total test force	F	N	**1471.0**	**0.2%**	2.9E+00	2.9E+00	-4.0E-02	4.6E-03
Indenter angle	α	°	**120**	**0.1**	1.0E-01	3.3E-03	1.3E+00	5.6E-03
Indenter radius	r	mm	**0.200**	**0.005**	5.0E-03	8.3E-06	1.5E+01	1.9E-03
Indentation depth	h	µm		**0.2**	2.0E-01	1.3E-02	5.0E-01	3.3E-03
Indentation velocity	v	µm/s	**30**	**10**	1.0E+01	3.3E+01	-2.0E-02	1.3E-02
Preliminary test force dwell time	t_0	s	**3**	**2**	2.0E+00	1.3E+00	1.0E-02	1.3E-04
Total test force dwell time	t	s	**4**	**2**	2.0E+00	1.3E+00	-7.0E-02	6.5E-03
Total								3.7E-02
Combined standard uncertainty $u(H)$								1.9E-01
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$							**0.38 HRC**	
Hardness	**20.0 HRC**							

Rockwell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Preliminary test force	F_0	N	**98.07**	**0.5%**	4.9E-01	8.0E-02	7.0E-02	3.9E-04
Total test force	F	N	**1471.0**	**0.2%**	2.9E+00	2.9E+00	-3.0E-02	2.6E-03
Indenter angle	α	°	**120**	**0.1**	1.0E-01	3.3E-03	8.0E-01	2.1E-03
Indenter radius	r	µm	**0.200**	**0.005**	5.0E-03	8.3E-06	3.0E+01	7.5E-03
Indentation depth	h	µm		**0.2**	2.0E-01	1.3E-02	5.0E-01	3.3E-03
Indentation velocity	v	µm/s	**30**	**10**	1.0E+01	3.3E+01	0.0E+00	0.0E+00
Preliminary test force dwell time	t_0	s	**3**	**2**	2.0E+00	1.3E+00	5.0E-03	3.3E-05
Total test force dwell time	t	s	**4**	**2**	2.0E+00	1.3E+00	-4.0E-02	2.1E-03
Total								1.8E-02
Combined standard uncertainty $u(H)$								1.3E-01
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$							**0.27 HRC**	
Hardness	**40.0 HRC**							

Rockwell - Influencing quantity X_i	Symbol	Unit	Value	Tolerance	a_i, type B	$u^2(x_i)$	c_i	$u_i^2(H)$
Preliminary test force	F_0	N	**98.07**	**0.5%**	4.9E-01	8.0E-02	5.0E-02	2.0E-04
Total test force	F	N	**1471.0**	**0.2%**	2.9E+00	2.9E+00	-2.0E-02	1.2E-03
Indenter angle	α	°	**120**	**0.1**	1.0E-01	3.3E-03	4.0E-01	5.3E-04
Indenter radius	r	µm	**0.200**	**0.005**	5.0E-03	8.3E-06	5.0E+01	2.1E-02
Indentation depth	h	µm		**0.2**	2.0E-01	1.3E-02	5.0E-01	3.3E-03
Indentation velocity	v	µm/s	**30**	**10**	1.0E+01	3.3E+01	3.0E-02	3.0E-02
Preliminary test force dwell time	t_0	s	**3**	**2**	2.0E+00	1.3E+00	4.0E-03	2.1E-05
Total test force dwell time	t	s	**4**	**2**	2.0E+00	1.3E+00	-3.0E-02	1.2E-03
Total								5.7E-02
Combined standard uncertainty $u(H)$								2.4E-01
Confidence level								95%
Coverage factor								2.0
Expanded standard uncertainty $U(H)$							**0.48 HRC**	
Hardness	**60.0 HRC**							

In the tables we can see, for different types of hardness scales, that some tolerances on the force, time, indentation measuring system or indenters can be enlarged without significant modifications of the associated uncertainties. These tolerance limits can be useful in the revision of the standards to guide the experts to characterize any single influence factor with the maximum possible tolerance to achieve the same value of uncertainty at the lower cost (in terms of instruments and controls).

3. CONCLUSION

The presented analysis demonstrates that is possible to reduce the uncertainty in hardness measurements, beginning from the possible elimination of the uncertainty at the level of international definitions and, consequently, with a reduction of uncertainties at the level of primary hardness standard machines. A summary of these improvements is shown in figures 2, 3 and 4.

Brinell scales are those have more benefits from the possible CCM-WGH definition, reducing his uncertainty of about 50%. Vickers scales are strictly more depending from the geometry of the indenter that is not easy to improve (especially for what concerns tip radius and line junction): in this case, leaving the tolerances on these parameters like they are, the improvement is only of about 0,1% on an uncertainty of about (2÷6)%. Rockwell C scale has more benefits in the low and high part of the scale, where is possible to reduce the uncertainty of about 0,1 HRC over (0,1÷0,4) HRC.

Moreover, this analysis allows the characterization of most significant factors and then the calculation of maximum tolerances to introduce in international standards in order to reduce the instrumentation and control procedures costs assuring the same uncertainty.

The analysis has be done on the most important Rockwell, Vickers and Brinell hardness scales, but it will be possible to extend the benefits easily to all other scales.

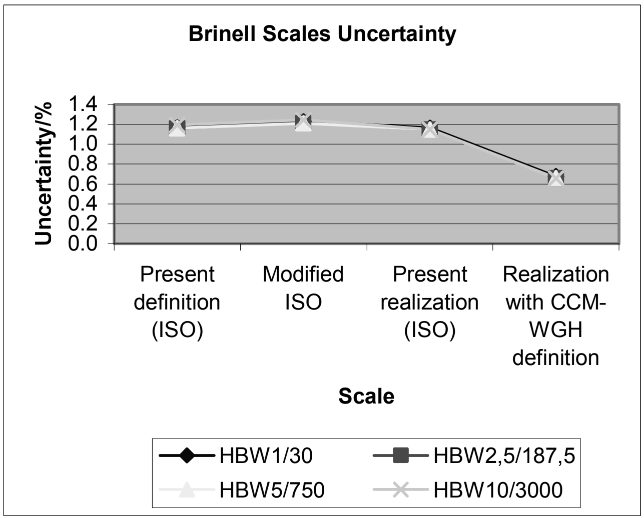

Fig. 2. Uncertainties of different definitions and realizations based on those definitions for some Brinell scales.

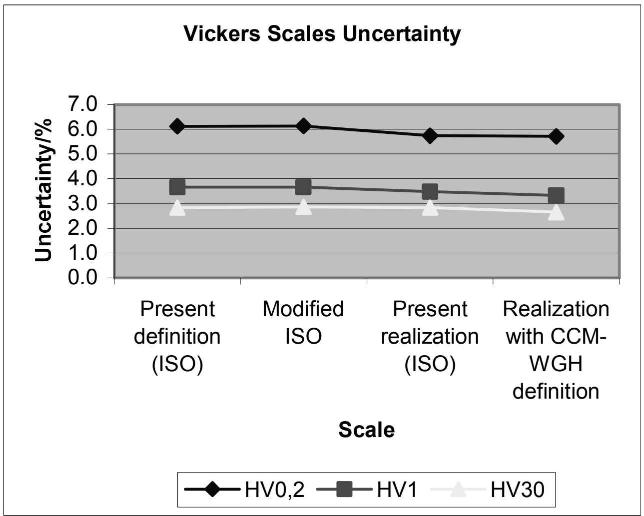

Fig. 3. Uncertainties of different definitions and realizations based on those definitions for some Vickers scales.

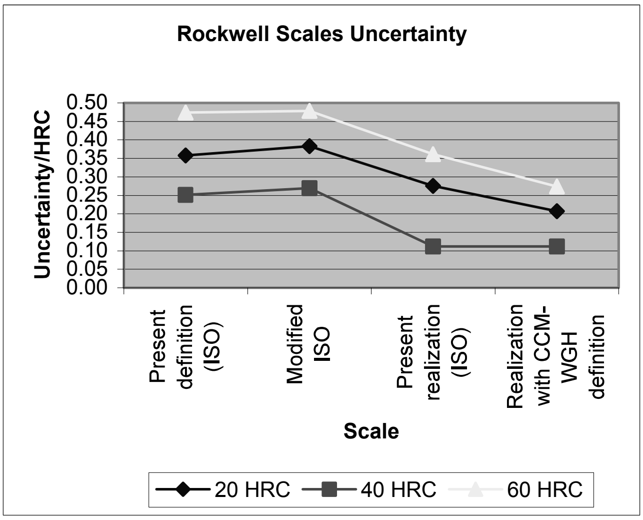

Fig. 4. Uncertainties of different definitions and realizations based on those definitions for Rockwell C scale.

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