

## ANALYSIS AND ESTIMATION OF POSSIBLE LARGE SYSTEMATIC ERROR IN BRINELL HARDNESS MEASUREMENTS

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**Abstract** – Brinell hardness measurements are widely used at industrial level. For the calculation of Brinell hardness values, the measurement of the diameter of indentations is necessary. In practice, the measurement of the image created by the optical systems used for the magnification of the indentation is usually carried out. The dimension of the indentation image depends by the optical system that, in practice, transform the real indentation in image using properties of light reflection.

The paper describe the effect of this influence parameter in Brinell hardness measurements in experiments carried out at hardness laboratory of Istituto Nazionale di Ricerca Metrologica (INRIM) (formerly Istituto di Metrologia “G. Colonnetti” – IMGC) with application to the data obtained at international comparison at the National Metrology Institutes level. Moreover, some methods for its evaluation and possible correction will be proposed.

**Keywords:** Brinell hardness, influence parameters, numerical aperture

### 1. INTRODUCTION

Brinell hardness measurements are widely used at industrial level since their beginning when eng. Brinell proposed the method at the 1900 Congress in Paris.

Brinell hardness method is defined, like other hardness scales, by an operational procedure that involves force, time, velocity and dimension of the indenter (hard metal ball); the formula that relates hardness with the other quantities is the following:

$$HBW = 0,102 \cdot \frac{2 \cdot F}{\pi \cdot D \left( D - \sqrt{D^2 - d^2} \right)} \quad (1)$$

where  $F$  is the applied force,  $D$  is the diameter of the ball indenter and  $d$  is the mean diameter of the indentation.

While  $F$  and  $D$  are quite easy to measure (or better to estimate), the measurement of the diameter of the real indentation is very difficult and never (at least at industrial level) carried out. Like for Vickers indentations, in place of the real physical measurement, the measurement of the image created by the optical systems used for the magnification of the indentation is usually carried out.

The dimension of the indentation image depends by the optical system that, in practice, transform the real

indentation in image using properties of light reflection. One of the parameters that are involved in this process is the so called Numerical Aperture of the light and of the lens used by the optical system.

This effect has been widely studied in the past, but, even if it can reach (or exceed) the same level of the declared uncertainty, its quantification in the measurement results is not easy. Moreover, being it not standardized, its influence should be directly included in the evaluation of the uncertainty of Brinell measurements.

### 2. PROBLEM

Analysing preliminary results of the last CIPM Hardness Brinell Key-Comparison (CCM.H.K2) [1], Pilot Laboratory concludes the report with the following sentences:

*“The deviations from Key Comparison Reference Value and the difference between institutes can not be explained by the reported uncertainty from each institute in many cases. This means that the uncertainties reported from each institute are underestimated...”*

*Results of the diameter measurement on artificial indentation show smaller difference between institutes compared to on indentations made by force application...*

*Therefore, it can be concluded that the large difference between institutes was caused by certain things relating to the three-dimensional diameter measurement which is NOT defined either in the protocol or ISO standard.”*

Looking for possible sources of these differences on measurements, at INRIM laboratory a deep analysis of the INRIM results of the Key Comparison has been carried out.

One of the possible sources is the numerical lens aperture (N.A.) effect. Named  $\gamma = \arcsin(\text{N.A.})$  the lens aperture angle and the illumination angle (for simplicity both equal), as is shown in fig. 1, when the observed surface is inclined of an angle  $\alpha < \gamma$  it appears bright, meanwhile when  $\alpha > \gamma$  it appears dark.

When a Brinell indentation is observed, the relative wide radii generated during the indentation process and the consequently different angle of the surface (fig. 2) can generate different indentation images. Since the image, and not the real physical indentation is measured, the dimension (diameter) can vary if a different N.A. is used for the image generation.

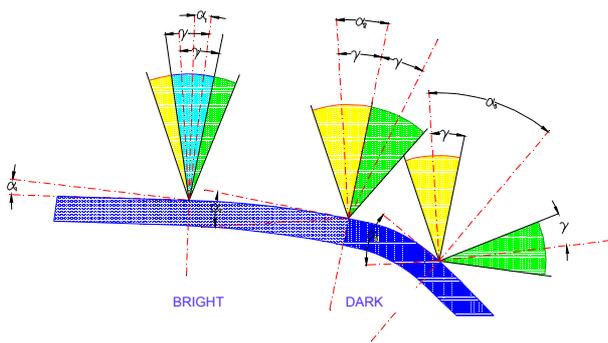


Fig. 1. Schematic drawing of illumination and observation cones on an inclined surface

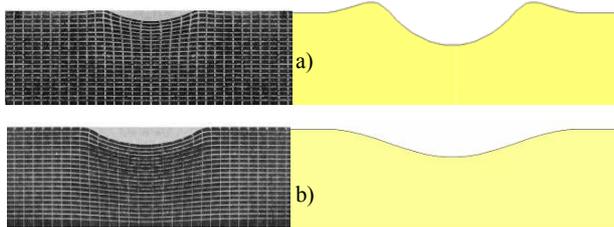


Fig. 2. Scheme of typical profile of Brinell indentation: a) ridging effect b) sinking effect

### 3. STATE OF THE ART

Numerical aperture effect is very well known in literature. Some investigation have been done in the past on Vickers and Knoop measurements [2, 3, 4, 5, 6, 7, 8] but few on Brinell measurements [8, 9].

At the same conclusions enunciated in the report of CCM.H.K2 comparison, were arrive past investigations. In detail, Barbato and Desogus [8] about twenty years ago, concluded that measurements of Brinell (and Vickers) indentations are the greatest contribution to the uncertainty in hardness and most of the effects of differences in optical microscopes are not taken into account by Standard specifications. They demonstrated also how significant the numerical aperture of the lens (and the position of the image focal plane) may be.

In particular, for Brinell measurements, they gave the results reported in fig. 3.

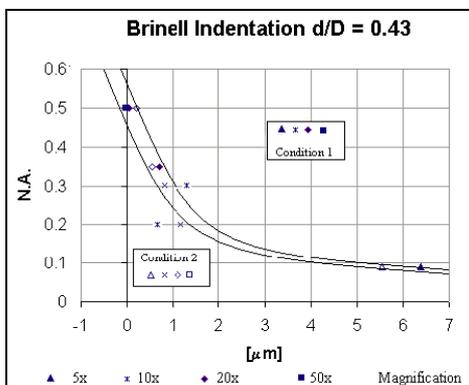


Fig. 3. Trend of Brinell indentation measurements at two focal plane positions and different magnifications [8]

From this investigation, carried on 200 HB2,5/187,5 indentation, possible differences up to about 6  $\mu\text{m}$  (3%) can be justified for using different N.A. (from 0,5 to 0,09).

Leigh, in his investigation [4], proposed a correction factors with an empirical formula indicating that the visibility error is proportional to  $1/(NA+0.3)$ .

Looking at the INRIM results to the CCM.H.K2 comparison at 250 HBW2,5/187,5, the difference from the Key Comparison Reference Value (KCRV) is about 5% using a N.A. of 0,07.

Premises seem to be promising for the amount of variations obtained by INRIM at CCM.H.K2 comparison.

The limit of the past investigations is that or they are limited to a specific scale and hardness value [8], or they are specific to the optical system used for the investigation [4].

For these reasons and with the aim to obtain a general formula for possible corrections, more investigations on this effect have been carried out at INRIM hardness laboratory.

### 4. EXPERIMENTAL DESIGN

The very simple experiment carried out was the measurement of different images obtained with different N.A. of lenses and illumination system (both equal for each experiment) of the same physical indentation for each scale and hardness level used at the CCM.H.K2 comparison. Results are reported in table I and in fig. 4.

TABLE I. Experimental design: differences of measurements in micrometers. 0,5 N.A. is taken as reference value.

Hardness/HB	Scale	N.A.				
		0,07	0,09	0,2	0,4	0,5
250	HBW1/30	7,9	5,7	1,0	-0,3	0,0
350	HBW1/30	6,5	5,3	2,0	1,0	0,0
450	HBW1/30	5,9	4,2	1,4	0,5	0,0
250	HBW2,5/187,5	17,6	8,5	1,2	-0,1	0,0
350	HBW2,5/187,5	15,1	8,1	2,2	0,8	0,0
450	HBW2,5/187,5	10,1	8,2	1,6	1,2	0,0
250	HBW5/750	33,7	23,2	5,9	1,4	0,0
350	HBW5/750	23,1	13,3	2,7	0,6	0,0
450	HBW5/750	14,9	8,5	1,7	0,7	0,0
250	HBW10/3000	52,5	37,5	5,8	1,3	0,0
350	HBW10/3000	35,4	24,7	4,4	-1,2	0,0
450	HBW10/3000	25,8	20,1	2,6	0,4	0,0

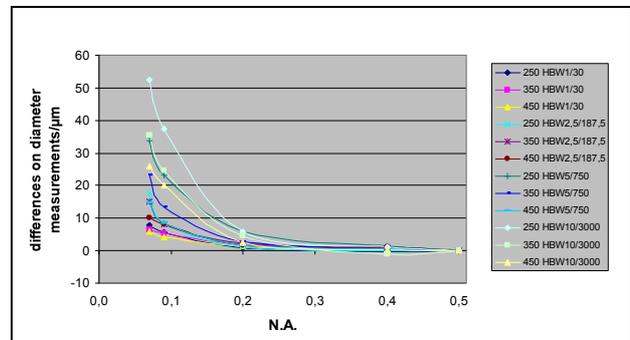


Fig. 4. Numerical Aperture effect on Brinell measurements: absolute differences (in micrometers)

As it is possible to see, results shown a correlation between N.A. and that differences in measurement depend by the hardness scale (different force and ball indenter diameter) and hardness level. The correlation become more evident if we plot the results as relative differences (fig. 5).

The first result observed from the experimental data is that greater differences are present when low (0,07 – 0,09) N.A. is used; increasing the N.A., measurements are most stable.

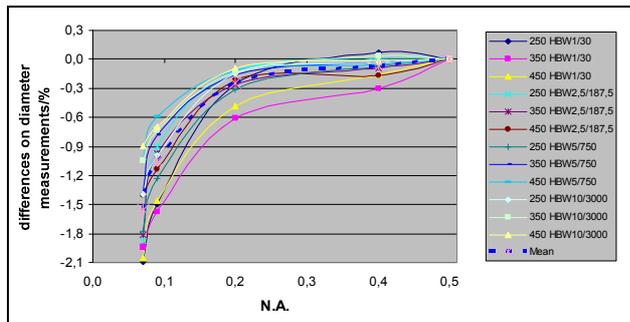


Fig. 5. Numerical Aperture effect on Brinell measurements: relative differences

Since the correlation between N.A. and differences in measurement is evident, an interpolation curve has been fitted using the least squared regression through experimental data. The first hypothesis of model was a polynomial curve of third degree on independent variable  $NA$  and first order on hardness level,  $HB$ , force,  $F$ , and diameter of ball indenter,  $D$ . Applying the regression analysis to the experimental data, the following equation has been calculated:

$$\Delta HB = 25,26(\pm 13,40)NA - 72,13(\pm 11,48)NA^2 + 66,50(\pm 2,84)NA^3 + 0,000509(\pm 0,000335)HB - 0,000257(\pm 0,000109)F + 0,1275(\pm 0,0382)D - 3,417(\pm 0,228) \quad (2)$$

The standard deviation of residuals is 0,21% and the correlation coefficient is 0,91.

Looking at the standard deviation of coefficients (in brackets), not all independent variables have the same level of meaningfully.

For simplifying the equation, a second model has been tried using only the most significant independent variables ( $NA$  and  $D$ ). The result is the following equation:

$$\Delta HB = 66,50(\pm 14,08)NA - 72,13(\pm 12,07)NA^2 + 25,26(\pm 2,99)NA^3 + 0,0400(\pm 0,0084)D - 3,089(\pm 0,1944) \quad (3)$$

The standard deviation of residuals is 0,22% and the correlation coefficient is 0,90.

Losing only 0,01% in the standard deviation of residuals, the second equation can be more easily used to calculate the theoretical differences due to N.A. in Brinell measurements.

In fig. 6 an example of application of the two different type of equations have been applied to the HBW2,5/187,5 scale at three different hardness levels.

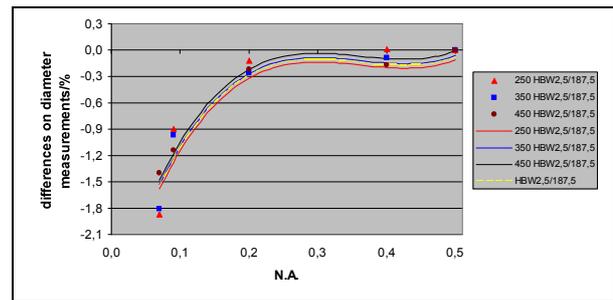


Fig. 6. Example of application of interpolation curves to experimental data (dots) of HBW2,5/187,5 scale: continuous lines for eq. 2, dot line for eq. 3

As we said before, the problem arise because the N.A. values to be used for the observation and measurement of Brinell indentations are not defined in the relative standards [11, 12, 13]; so, at the present, is not possible to define which is the correct measurement (even if considerations on the indentation border location can be made, not in easily way, considering the contact points between indenter ball and block surface).

As observed at the beginning, high N.A. values correspond most stable measurements. For this reason, the high (0,5) N.A. can be used as reference value. So, the proposal is the use of the eq. 2 (or the more simple eq. 3) to normalize the HB measurements.

An exercise of normalization has been applied to the INRIM data obtained during the CCM.H.K2 Comparison. In Table II the provisional Reference Values are presented, in table III the INRIM results are presented and in table IV the normalization of INRIM results are presented.

The uncertainty of the normalized INRIM values have been recalculated combining the declared uncertainty with the standard deviation of the interpolation curves.

In fig. 7 the Differences from the KCRVs of normalized INRIM results are presented.

TABLE II. Provisional CCM.H.K2 Comparison Reference Values

Scale	Hardness level	KCRVs/HBW	U/%
HBW1/30	250	250,79	0,28
HBW2,5/187,5	250	256,59	0,32
HBW5/750	250	249,93	0,21
HBW1/30	350	359,22	0,33
HBW2,5/187,5	350	356,20	0,28
HBW5/750	350	361,12	0,21
HBW10/3000	350	357,29	0,38
HBW1/30	450	449,05	0,40
HBW2,5/187,5	450	453,73	0,26
HBW5/750	450	454,80	0,20
HBW10/3000	450	454,17	0,20

TABLE II. INRIM results obtained at the CCM.H.K2 Comparison

Hardness level	N.A.	d/ $\mu$ m	H/ HBW	U/%
250 HBW1/30	0,09	387,93	243,89	1,15
250 HBW2,5/187,5	0,07	968,59	244,54	1,06
250 HBW5/750	0,07	1953,48	240,30	1,00
350 HBW1/30	0,09	323,66	354,82	0,96
350 HBW2,5/187,5	0,07	816,35	348,41	1,11
350 HBW5/750	0,07	1623,18	352,63	0,88
350 HBW10/3000	0,07	3238,29	354,44	0,99
450 HBW1/30	0,09	289,05	447,41	1,00
450 HBW2,5/187,5	0,07	721,47	448,88	0,95
450 HBW5/750	0,07	1441,79	449,62	0,91
450 HBW10/3000	0,07	2870,64	453,77	0,86

TABLE IV. Normalization of INRIM results obtained at the CCM.H.K2 Comparison

Hardness level	N.A.	Correction/%	d <sub>corr</sub> / $\mu$ m	H <sub>corr</sub> /HBW	U/%
250 HBW1/30	0,09	-1,48	382,2	251,57	1,23
250 HBW2,5/187,5	0,07	-1,84	950,81	254,15	1,15
250 HBW5/750	0,07	-1,75	1919,35	249,29	1,10
350 HBW1/30	0,09	-1,55	318,64	366,41	1,05
350 HBW2,5/187,5	0,07	-1,78	801,8	361,53	1,19
350 HBW5/750	0,07	-1,34	1601,42	362,55	0,99
350 HBW10/3000	0,07	-1,04	3194,86	364,42	1,08
450 HBW1/30	0,09	-1,44	284,89	460,89	1,09
450 HBW2,5/187,5	0,07	-1,38	711,49	461,85	1,05
450 HBW5/750	0,07	-1,02	1427,02	459,18	1,02
450 HBW10/3000	0,07	-0,89	2841,24	463,42	0,97

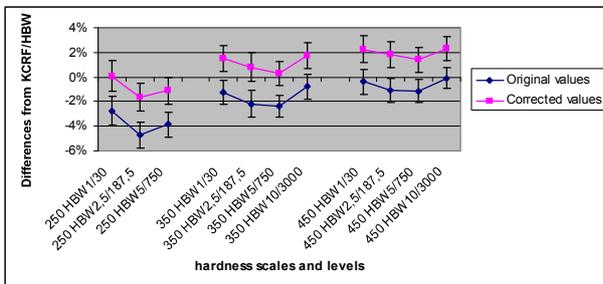


Fig. 7. Differences from the KCRV of normalized INRIM hardness measurements obtained at CCM Hardness Brinell KC

Applying the normalization curve to the INRIM hardness measurement of CCM.H.K2 Comparison, the results are correctly shifted when measuring 250 HBW, partially shifted when measuring 350 HBW and not correctly shifted when measuring 450 HBW.

Before any conclusion, it is necessary the knowledge of the N.A. used by others participants to the CCM.H.K2 Comparison for calculating normalized KCRVs. In fact, the normalized data must be analysed comparing new normalized KCRVs.

A possible hypothesis is that the majority of participants have used low N.A. when measuring 250 HBW and only few when measuring 450 HBW. Following this hypothesis and for pure academic exercise, a new KCRF has been calculated using, as reference N.A. of the KCRVs, 0,5 for

250 HBW, 0,2 for 350 HBW and 0,1 for 450 HBW. Results are presented in fig. 8.

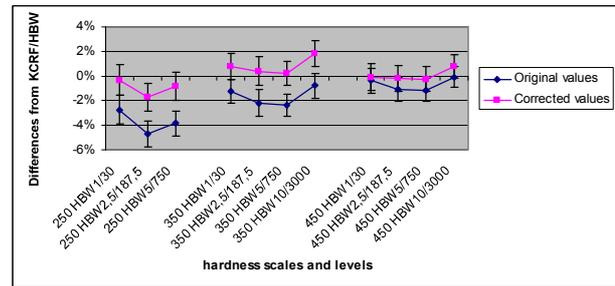


Fig. 8. Differences from hypothetical normalized KCRVs of normalized INRIM hardness measurements obtained at CCM.H.K2 Comparison

In this hypothetical case, considering also uncertainty of KCRVs that are, as reported in table II, between (0,2÷0,4)%, all results would be compatible.

So, for a better understanding of the problem it is absolutely necessary re-elaborate the data of the KC normalizing all measurements and recalculating KCRVs.

## 5. CONCLUSION

An important influence parameter (numerical aperture) of Brinell hardness measurements has been investigated. It is not taken into account in any relevant standards so, at the present, it is not possible to apply any correction for this parameter to the Brinell measurements. At the present, the limit of the uncertainty in Brinell measurements is determined by the possible variations in measurement due to the N.A. effect: it is about 2÷3%.

However, when the requested uncertainty of measurement is lower than 2÷3% (surely for the calibration of hardness reference blocks), a possible normalization of Brinell measurements is possible using the normalization curves calculated by experimental data. Otherwise, uncertainty in measurement better than 2÷3% cannot be obtained if the N.A. effect is correctly included in the uncertainty budget.

## REFERENCES

- [1] Koichiro Hattori, G.W. Bahng, "Brinell Key Comparison CCM.H-K2", Final Report, Draft A, Oct. 2005
- [2] Guidelines to the determination of the uncertainty of the Brinell and Vickers measuring method. PTB/5.21 note, 8.9.99.
- [3] Shin S, Hida N and Yano H., "Establishment of Brinell hardness and evaluation error", NRLM, Tokyo, Japan.
- [4] Leigh I C., "The micro-indentation hardness test: The practical realization of a standard", PhD thesis, University of Surrey, 1983.
- [5] Tarasov L P and Thibault N W., "Determination of Knoop hardness numbers independent of load", Trans Am Soc Metals. 35, 1945.
- [6] Thibault N W and Nyquist H L., "The measured Knoop hardness number of hard substances and factors affecting its determination", Trans Am Soc Metals. 38, 1947.

- [7] Hida N and Yamamoto K., "On the determination of absolute values of diagonal length of Vickers indentation", Bulletin of NRLM, No 25, Tokyo, Japan, 1970.
- [9] Barbato G and Desogus S., "Problems in the measurement of Vickers and Brinell indentations", Measurement, v4, No4, Oct-Dec 1986, pp137-147.
- [8] Martins A R, Paciornik S and Pereira J A S. "Brinell hardness : Image analysis and uncertainty", Proc. XVI IMEKO World Congress, Vienna, Austria. 25-28 September 2000.
- [10] ISO 6506-1:2005, "Metallic materials -- Brinell hardness test -- Part 1: Test method".
- [11] ISO 6506-2:2005, "Metallic materials -- Brinell hardness test -- Part 2: Verification and calibration of testing machines".
- [12] ISO 6506-3:2005, "Metallic materials -- Brinell hardness test -- Part 3: Calibration of reference blocks".

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