Metrological Characterization Of Optical Measuring System For Hardness Indenters

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Abstract
The verification of the geometry of Rockwell indenters has been widely studied in the past and, at the present, it is one of the most important tasks (in the uncertainty budget of hardness measurements) in discussion in many international organizations involved in the hardness field. The new measuring system designed in IMGC and developed in cooperation with AFFRI has been characterized and the results of the calibration are presented. The uncertainty evaluation has been calculated following the ISO guide on uncertainty evaluation. At the end, the results of the intercomparison between the new instrument and the instrument used up to now in IMGC laboratory, completely different from the point of view of measurement methodology, are presented.

1 Introduction

The described measuring system is a new IMGC design developed in cooperation with AFFRI (fig. 1). It can be used to measure the geometrical characteristics of the Rockwell and Vickers diamond indenters that are one of the main contributions in the uncertainty in hardness measurements [1, 2, 3]. It is based on the interferometric image analysis of different sections of the indenters. Special algorithms are implemented to obtain, from a section of the interferometric images, the indenter profile reconstruction [4].
The main characteristics of the measuring system are an adequate uncertainty to calibrate the indenters used in hardness testing machines [5] and in the calibration of hardness reference blocks [6], fast measurement execution and relatively low cost.
These characteristics allow this instrument to be easily used in Primary Metrological Institutes laboratories, Calibration laboratories and Industrial laboratories.

Figure 1 - Optical Measuring System for the calibration of the geometrical characteristics of diamond hardness indenters. The system is based on the interferometric image analysis of different sections of the indenters. It is composed of an optical microscope with interferometric lens, a rotating table for the indenters support (motorised by a DC motor and equipped with a calibrated angular encoder), a digital CCD camera and software specially developed for the analysis and measurement.

2 Calibration

The operation of characterization consists in the calibration of several devices composing the instrument to assure the traceability to the national standards for length and angle.

Also implemented algorithms used to elaborate the images are evaluated taking into account their influence in the uncertainty budget.

2.1 Calibration of the magnification of the lens

The optical system is composed by an optical microscope with interferometric lens used to generate the interferometric images and a digital CCD camera used to acquire the interferometric images. The mean value of the dimension of the elementary pixel in X axis has been calculated observing and measuring the optical field against a scale of a stage micrometer. Having measured the full field of the image equal to 441 μm and being the resolution of the CCD camera (in X direction) of 1300 pixels, the X dimension of the elementary pixel is (339,2±0,8) nm/pixel, taking in consideration the calibration uncertainty of the stage micrometer (U=±0,5 μm) and the repeatability of the measurements.

2.2 Calibration of the angular encoder

The angular encoder is used to measure the angle of the image acquisition. A twelve faces prism with an uncertainty lower than 0,002° has been used to calibrated the angular encoder (fig. 2). For the zero reference of each face, the interferometric image with null fringes has been used. The resolution of the encoder is 0,01° and for the calibration it was estimated that the uncertainty is lower than the resolution.

Figure 2 – Detail of the calibration of the angular encoder.
A twelve faces prism has been used to calibrate the angular encoder. For the zero reference of each face, the interferometric image with null fringes has been used.

2.3 Calibration of the wavelength of the light

The interferometric images are generated using the light of the microscope illumination system filtered with a filter of (515±3)nm wavelength. The uncertainty declared in the calibration certificate of the producer has been used as reference.

3 Optical errors

Images used to reconstruct the indenter profile are created by the interferometric lens based on the wave-like theory of the light [7]. Essentially the objective is composed by a series of lenses for the magnification of the image and by a reference plane. On the principle of the Michelson interferometer, the fringes are generated by means of optical interference. With this type of objective, observing the spherical tip of the Rockwell indenter, pseudo-circular fringes of interferences, like Newton rings, are generated. The measurement algorithm is based on the determination of the distance of any singular observed point, having the information on the grey level variation. From the wave like theory of the light, between one and the subsequent fringe, the variation of the depth of the observed surface is half of the wavelength of the light used to illuminate the surface ($\lambda/2$). Starting from the optical image, through the luminance profile, it is possible to reconstruct the profile of the observed surface.
But, because the interference is created between a reference plane and a spherical surface (in the case of the spherical tip measurement of Rockwell indenter) or a tilted surface (in the

case of angle measurement of Vickers and Rockwell indenters), the images are affected by an error due to the angle of the reflected light from the surface (fig. 4a, b) [8]. The effect of this error is evidenced as a deformation of the X axis (Δx).

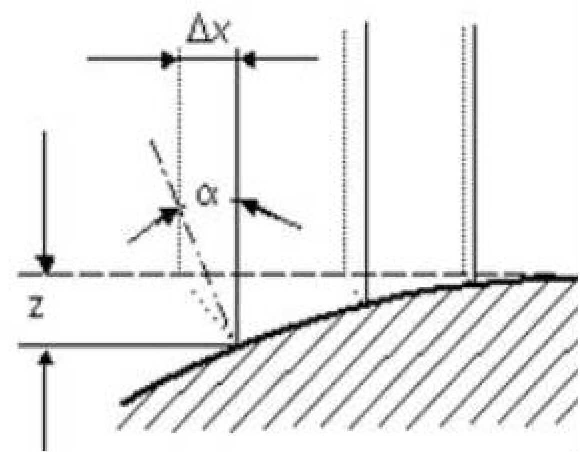

Figure 4a – Optical error in the interferometric images due to the interference between a reference plane and a spherical surface (spherical tip measurement of Rockwell indenter).

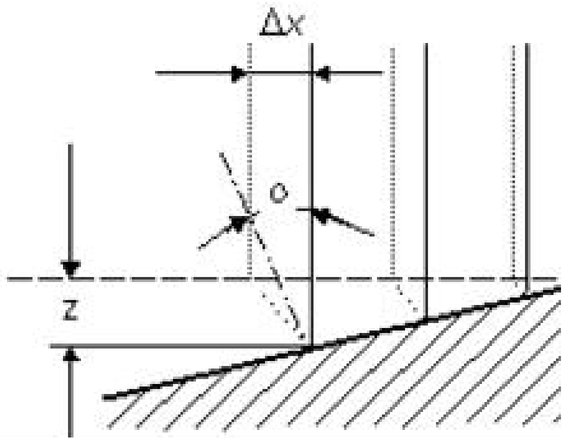

Figure 4b – Optical error in the interferometric images due to the interference between a reference plane and a tilted surface (angle measurement of Vickers and Rockwell indenters).

3.1 Error on radius measurement

In the case of radius measurement, the observed profile is affected by an error that modifies the real profile (fig. 5). If the error is not compensated, the result on the calculation of the interpolated radius (using the least squared method) gives a systematic error of 2,65 µm (with an observation field of ±20 µm): moreover, due to the elliptic shape of the modified profile, we obtain residuals like the ones shown in fig. 6.

3.2 Error on angle measurement

Also in this case we observe a modified profile (fig. 7). Due to the direct proportionality of the error, in this case and for any angle of observation γ, we have only a systematic error on the angle measurement α (fig. 8) without any distortion

3.3 Correction of the optical errors

To correct the errors, theirs functions have been determined, for the radius (fig. 9) and angle measurements, with a simple geometrical analysis.
The analytic functions are the following:

$$\Delta x = 2{,}55\ \text{E-}05\ x - 5{,}03\ \text{E-}05\ x^3, \quad (1)$$

that allows to correct the X axis for each image acquisition and analysis in the case of radius measurement, and

$$\Delta x = 1{,}55\text{E-}01 x \quad (2)$$

that allows to correct the X axis for each image acquisition and analysis in the case of angle measurement. Due to the linearity of the function, in this last case it is also possible to correct directly the result of the angle measurement, after the calculation, with the following formula:

$$\Delta\alpha = 1{,}54\ \text{E-}02\gamma - 6{,}49\ \text{E-}03\ \gamma^2 \quad (3)$$

where γ is the angle of observation.

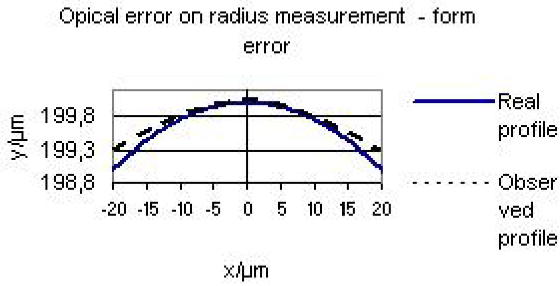

Figure 5 – Form error on radius measurement due to optical error in the generation of interferometric images between a reference plane and a spherical surface.

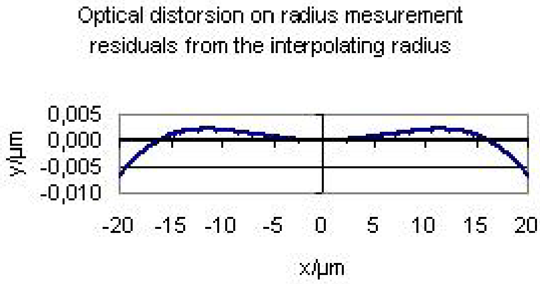

Figure 6 – residuals of the interpolation (using the least squared method) when the error is not compensated.

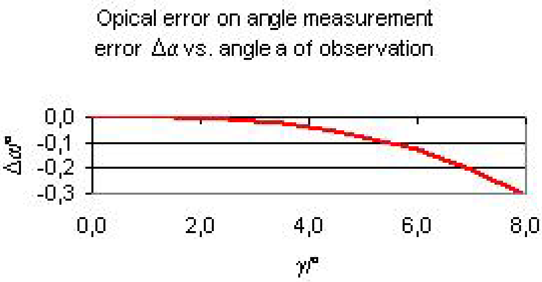

Figure 8 – Effect of optical error on angle measurement. Because the indenter rotates during the measurement, the systematic error depends on the angle of observation.

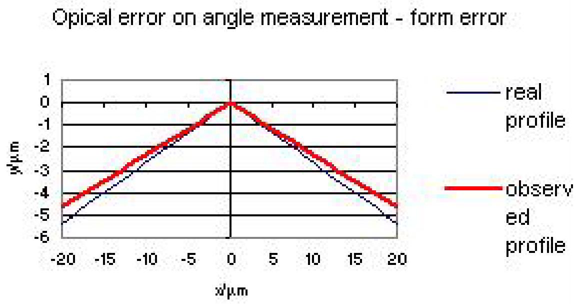

Figure 7 – Form error on angle measurement due to optical error in the generation of interferometric images between a reference plane and a tilted surface (15°).

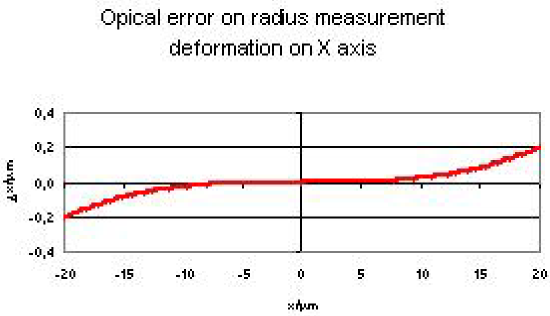

Figure 9 – Correction for the optical error on radius measurement

4 Uncertainty budget

Following the ISO [9] and EA [10] guides in this field, the uncertainty budget on radius and angle measurements for Rockwell indenters have been calculated as reported in tables 1 and 2. Due to the complex evaluation of the mathematical model in the composition of the images, the measurement of the radius has been expressed as a function of the measurement independent variables as follows:

$$R = f(\lambda, d) \quad (4)$$

and, for the angle:

$$\alpha = f(\lambda, d, \gamma) \pm \Delta\alpha \quad (5)$$

Table 1 - Evaluation of the uncertainty budget in the radius measurement.

x_i Simb.	x_i Val.	x_i Units	Standard uncertainty s_i	a_i	$u^2(x_i)=\frac{a_i^2}{3}$	Sensitivity coefficients $c_i=\frac{\Delta R}{\Delta x_i}$	Contributions to $u^2(R)\approx \approx \sum_{i=1}^{N} u_i^2(R) = = \sum_{i=1}^{N} c_i^2 u^2(x_i)$	Degrees of freedom νi
λ	0,515	µm		3,0E-03	3,0E-06	-3,6E+02	3,9E-01	30
D	0,3392	µm/pixel	3,9E-04		1,5E-07	1,1E+03	1,7E-01	5
reproducibility		µm	1,0E-01		1,0E-02	1	1,0E-02	9
Correction		µm	1,7E-04		2,9E-08	1,2E+01	4,1E-06	100
				Total			5,7E-01	µm^2
				Standard uncertainty			0,76	µm
				Degrees of freedom			29	
				Confidence level			95%	
				Coverage factor			2,05	
				Expanded uncertainty			**1,55**	**µm**

Table 2 - Evaluation of the uncertainty budget in the angle measurement.

x_i Simb.	x_i Val.	x_i Units	Standard uncertainty s_i	a_i	$u^2(x_i)=\frac{a_i^2}{3}$	Sensitivity coefficients $c_i=\frac{\Delta R}{\Delta x_i}$	Contributions to $u^2(R)\approx \approx \sum_{i=1}^{N} u_i^2(R) = = \sum_{i=1}^{N} c_i^2 u^2(x_i)$	Degrees of freedom νi
λ	0,515	µm		3,0E-03	3,0E-06	5,8E+00	1,0E-04	30
D	0,3392	µm/pixel	3,9E-04		1,5E-07	-8,9E+00	1,2E-05	5
γ	0÷8	°		5,0E-03	8,3E-06	1	8,3E-06	3
Δα	0,005	°		5,0E-03	8,3E-06	1	8,3E-06	10
reproducibility		°	1,0E-02		1,0E-04	1	1,0E-04	9
Correction		°	8,6E-03		7,5E-05	3,8E-03	1,1E-09	100
				Total			2,3E-04	°^{2}
				Standard uncertainty			0,02	°
				Degrees of freedom			35	
				Confidence level			95%	
				Coverage factor			2,03	
				Expanded uncertainty			**0,03**	**°**

5 Verification of radius measurement

To verify the uncertainty budget, a ruby sphere of (200±0,1) µm radius has been measured (fig. 10). The result of (200,5±0,3)µm, expressed as the mean value ± the standard deviation of four cross sections measurements, confirm the expanded uncertainty of 1,55 µm.

6 Comparison

The radius measurement has been verified also comparing the measurement obtained with the other instrument used up to now in IMGC laboratory, completely different from the point of view of measurement methodology [11].

The differences obtained in the radius measurement of a good Rockwell indenter (fig. 11) are 0,5 µm for the mean value and a maximum of 1,0 µm for the single cross section measurements.

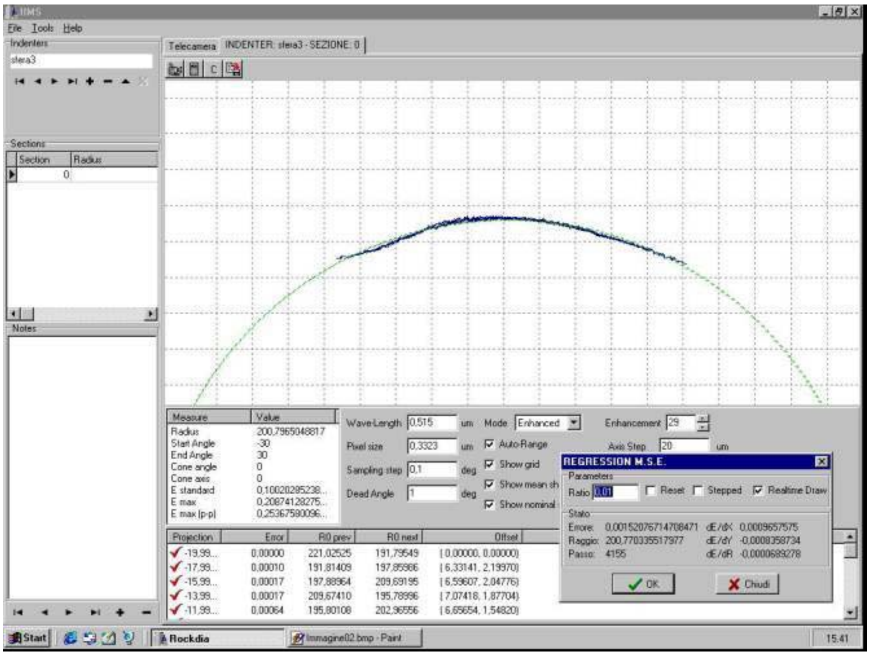

Figure 10 – Measurement results of a cross section of the ruby sphere used to verify the uncertainty budget evaluation in the radius measurement. Variations from the nominal value are presented In the picture enhanced 29 times the scale.

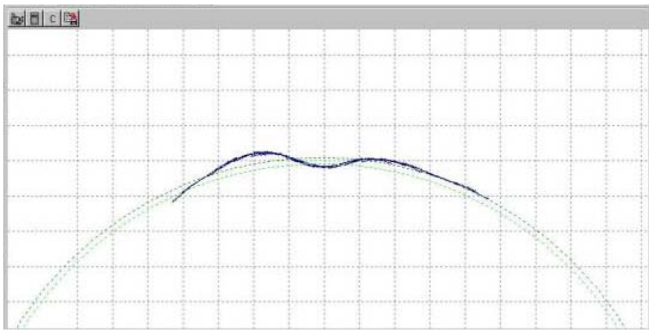

Figure 11 – Section profile of a good Rockwell indenter. Variations from the nominal value are presented In the picture enhanced 29 times the scale.

7 Conclusion

The metrological characteristics of the measuring system, previously evaluated with the uncertainty budget calculation and experimentally verified with a reference standard (for radius measurement) and confirmed by the internal comparison with the previous instrument, allow us to use it for the calibration of diamond indenters, both for industrial hardness machines and calibration hardness machines.
As shown by the budget evaluation of uncertainty, one of the most important contribution is the uncertainty of the wavelength of the light used to generate the interferometric images. A market investigation should be done to verify if better filters can be purchased.

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