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Considerations to the hardness Brinell measurement using optical equipment

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Abstract

A comparison of the results obtained applying the traditional methodology to measure the Brinell hardness value with different optical equipment has been performed. The results show that the measurements on Brinell hardness indentation give neither satisfactory results, nor reproducibility nor precision with respect to certificated values. The fundamental reason is the lack of definition on the indentation edge, where the Brinell indentation diameter should be measured. This causes a high dispersion of the diameters measured with different instruments, operators or measurement parameters.
In this work, we propose an alternative measurement methodology using confocal microscopy, which allows to determine a unique indentation edge. This methodology is of high interest for certification of hardness reference blocks because the results are independent of the measuring instrument and the operator.

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1. Introduction

Hardness represents the surface resistance that a material opposes to permanent deformation, both deformation by scratching and by surface penetration. This value may be determined by different procedures like scratching,

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rebound or static indentation. In general, these methods are quick, economical and minimally destructive procedures, and therefore represent a common resource for the acceptance, characterization and selection of materials.

The hardness tests most commonly used for metallic materials are the static indentation procedures, such as Brinell, Rockwell, Vickers, etc.

The procedure to measure the Brinell hardness is defined by the series of standards ISO 6506 [1]. Standard ISO 6506-1: 2014 [1] states that the test is performed by applying a force with a ball indenter on the surface of a test block under specific conditions that vary depending on the material that is tested. The Brinell hardness value is a function of the indenter diameter D , the test force F and the mean diameter of the indentation d , which is obtained from two indentation diameters measured at 90°. It is worth noting that the reference standards do not specify the instrument and/or the procedure to be applied for these measurements. Optical measurement is one of the methods most frequently used.

Traditionally the size of the indentation has been determined by profile projectors or optical microscopes. In these cases, the operator detects the edge of the indentation to perform the diameter measurement, but operator intervention and modification of focus or illumination may lead to significant variations in the indentation measurement [2].

Today measurements are usually made by optical systems with an integrated camera that amplify the indentation and provide an image of it. The study of the image is made automatically by using image analysis systems that remove completely the influence of the operator or with semi-automatic systems that allow the user to perform the final adjustment.

2. Experimental procedure

This work presents a comparison of the results obtained using the traditional methodology with different optical equipment. The comparison is performed with three optical tools commonly used to measure the diameter of a Brinell indentation: a profile projector, a CNC optical measuring machine and a manual vision measuring machine (Fig. 1). Measurements are made on the diameters of two Brinell reference blocks of 499.5 HBW 5/750 and 201.8 HBW 2.5 / 187.5 with UKAS calibration certificate, each one with five indentations.

The calibration certificate of the hardness reference blocks indicates the mean diameter d of each indentation and the block hardness derived from the mean of its five indentations. The first block hardness is 499.5 HBW 5/750, with an expanded calibration uncertainty (k=2) of 1.5% HB for the hardness value and 3 μm for the indentation size. The second block hardness is 201.8 HBW 2.5/187.5 with an uncertainty (k = 2) of 3.03 HB for the hardness value and 3 μm for the diameter.

It should be noted that just like the Brinell hardness standards [1] do not define the edge point where the diameter measurement shall be performed, the calibration certificates of the reference blocks do not provide any information on this subject. This lack of definition is seriously prejudicial for the reproducibility of measures, as demonstrated by this experimental study.

Fig. 1. Employed optical instruments.

For the three instruments, the adequacy of the measuring system for the indentation Brinell diameter according to ISO 6506-2: 2014 [3] was checked initially by calibrated circular and/or longitudinal standards. The indentation diameter is then measured and factors such as the measured value, the repeatability of the measurements, the measurement time and the measurement difficulty are assessed.

2.1. Profile projector

Diameter measurements are performed with an Orama 300V projector with a resolution of 1 μm and calibration uncertainty (k = 2) of 2 μm on the X and Y axes. Maximum available amplification, 50X, is used to facilitate the focusing of the indentation and the alignment the indentation edge with the axes of reference. Episcopic illumination is used on the sample, trying to illuminate the indentation uniformly to avoid shadows that may alter measurements.

The diameter measurement is performed in two perpendicular directions, X and Y, that coincide with the axis of the profile projector and with the directions of measurement established in the reference blocks. Measurements are repeated 10 times and the mean diameter of the indentation and the experimental standard deviation are obtained. The absolute and relative deviations of the mean diameters from the certified values [3] are also calculated.

Table 1 and Table 2 show the results obtained for three indentations of the Brinell reference block 201.8 HBW 2.5 / 187.5 and 499.5 HBW 5/750, respectively.

It is worth noting that the indentation diameter obtained for the 201.8 HBW 2.5/187.5 reference block (Table 1) is in all cases higher than the certified value with an average deviation of approximately -12 μm . On the other hand, the indentation diameter obtained for the 499.5 HBW 5/750 reference block (Table 2) is always higher than the certified value with an average deviation of approximately -3 μm .

Table 1. Results of 201.8 HBW 2.5/187.5 indentation diameters with profile projector.

Sample	Axis	s (μm)	d (mm)	Δd (μm)	Δd_{rel} (%)
1	X	1.45	1.0713	-12.10	1.1
	Y	1.57			
2	X	2.06	1.0772	-14.75	1.4
	Y	0.70			
3	X	0.84	1.0744	-9.00	0.8
	Y	1.40			

Table 2. Results of 499.5 HBW 5/750 indentation diameters with profile projector.

Sample	Axis	s (μm)	d (mm)	Δd (μm)	Δd_{rel} (%)
1	X	2.12	1.3776	-5.75	0.4
	Y	1.34			
2	X	2.20	1.3754	-0.85	0.1
	Y	3.38			
3	X	2.11	1.3716	-2.05	0.1
	Y	2.66			

It is observed that significant deviations from the certified value are obtained in both blocks. The main reason for this deviation is estimated to be that the measurements are performed on a different indentation edge than that used during the calibration process. In addition, other possible causes are considered such as the low amplification of the objective and the difficulties to illuminate the indentation edge without reflections and shadows that may disturb the measurement result.

It has been demonstrated that these indentations have a sharp curvature change on the edge area, which leads to a difficult illumination with light sources directed at the sample. This problem becomes more important on the Brinell reference block 201.8 HBW 2.5/187.5 because the indentations are smaller and it presents a greater pile-up in the indentation edge, which causes too high relative deviations, exceeding the value of 0.5% allowed by the standard [3].

The results obtained demonstrate the difficulties inherent to the measurement of the Brinell indentation diameter with large pile-up or sink-in in comparison with its diameter, where the indentation edge may be defined at different heights, with its consequent impact on the diameter measurement.

2.2. CNC optical measuring machine

The used instrument is a CNC optical measuring machine model O-Inspec332 of Zeiss that has a dual technology for contact or optical measurements. With the procedures described in [4, 5] the machine was calibrated and traceability was given to the measurements. Measurements presented in this section have an uncertainty (k = 2) of 1.5 μm .

The equipment has four different types of illumination: ring, mini ring, coaxial and transmitted light. It incorporates Calypso software to take measurements and to detect edges. Optical measurements of the indentation diameter are carried out with amplification of 3.2X to obtain the measurements in static mode, without displacements of the measurement table or composition of images.

Automatic detection of the indentation edge and auto focus with different types of illumination, intensities and measurement strategies are performed in order to check their influence on the diameter value. The indentation diameter is obtained by a mathematical adjustment that approximates the edge points to a circumference using least square procedure. Measurements are repeated 5 times and the mean diameter of the indentation and the experimental standard deviation are calculated.

Table 3 and Table 4 show the results obtained from the measurement of one of the indentations of the Brinell hardness reference blocks 201.8 HBW 2.5 / 187.5 and 499.5 HBW 5/750, respectively, with the CNC optical measuring machine, by varying the type and intensity of illumination and the measurement strategy: Inside-out (IO) or outside-in (OI). The standard deviation of the five measurements and the relative deviation of the obtained diameter from that indicated in the calibration certificate of the hardness reference block are also shown.

Table 3. Relative deviations in diameter measurement for 201.8 HBW 2.5/187.5 with CNC optical measuring machine.

Lighting type	Light intensity (%)	Strategy	s (µm)	d (mm)	Δd (µm)	Δd_{rel} (%)
Ring	14	IO	0.66	1.05552	9.88	-0.9
		OI	0.05	1.07586	-10.46	1.0
	9	IO	0.51	1.05722	8.18	-0.8
		OI	0.09	1.07604	-10.64	1.0
Mini-ring	22	IO	0.05	1.06366	1.74	-0.2
		OI	0.38	1.08918	-23.78	2.2
	34	IO	0.10	1.0632	2.2	-0.2
		OI	0.25	1.0865	-21.1	2.0
Coaxial	2.5	IO	0.11	1.11734	-51.94	4.9
		OI	0.15	1.11524	-49.84	4.7
	5	IO	0.95	1.08148	-16.08	1.5
		OI	0.84	1.08066	-15.26	1.4

It is observed that for both reference blocks, there is a great variability in the measurement, with the value of the diameter dependent on the illumination type, the intensity and the measurement strategy applied. For both reference blocks, maximum and minimum relative deviations are obtained with coaxial illumination and with mini-ring illumination, respectively.

For the 201.8 HBW 2.5/187.5 reference block, it is discerned that the indentation edge that was used during the calibration is within the range of measurements made with IO and OI strategies, for the ring and mini-ring illuminations. The IO strategy gets the result closest to the detected edge during the calibration. This reference block, as previously stated, has a rather high pile-up, so significant differences appear in the measurements depending on the height of the edge where the focus is located. However, for reference block 499.5 HBW 5/750, which has a low pile-up, the measurement strategy is less significant.

Table 4. Relative deviations in diameter measurement for 499.5 HBW 5/750 with CNC optical measuring machine.

Lighting type	Light intensity (%)	Strategy	*s* (μm)	*d* (mm)	Δ*d* (μm)	Δd_{rel} (%)
Ring	9	IO	0.09	1.36124	8.26	-0.6
		OI	0.16	1.35780	11.70	-0.9
Mini-ring	45	IO	0.14	1.36130	8.20	-0.6
		OI	0.16	1.37382	-4.32	0.3
Coaxial	2.5	IO	0.41	1.38396	-14.46	1.1
		OI	0.25	1.38438	-14.88	1.1

Based on the results herein presented, it is considered that the vision system of this measuring machine is able to determine the Brinell indentation diameter of similar samples, using mini-ring illumination with inside-out strategy for high pile-up and outside-in strategy for low pile-up. However, these considerations may not be valid to reproduce the hardness measurements from other calibration laboratories, because depending on the equipment used and its measurement characteristics, different values of the diameter are measured by locating the focus on a different boundary of the edge.

2.3. Manual vision measuring machine

The third equipment used is a Tesa Visio 300 manual vision-measuring machine with incremental optoelectronic rules allowing a resolution of 1 μm. It is equipped with a motorized zoom that allows amplifications from 0.7X to 4.5X, and has two episcopic light sources (annular and coaxial) and a diascopic lighting. With the procedures described in [4, 5] the machine was calibrated and traceability was given to the measurements. Measurements presented in this section have an uncertainty (k = 2) of 3 μm.

The measurements of the reference indentation are made with a 3X amplification that allows the machine to acquire the complete image of the indentation, avoiding stitching processes. Coaxial illumination is used because it provides the best definition of the Brinell indentation edge, avoiding shadows that alter measurements. A manual focus is performed and enough illumination intensity is selected, avoiding saturation of the image. The automatic detection of the edge points allows the determination of the indentation diameter from the approximate circumference. The measurements are repeated 5 times and the mean diameter is obtained.

Table 5 and Table 6 show the results for the indentations Nº 3 of the hardness reference blocks 201.8 HBW 2.5/187.5 and 499.5 HBW 5/750, respectively, using different lighting intensities and measurement strategies. The standard deviation of the measurements and the nominal deviation of the diameter respect to the calibration certificate of the reference block are also shown.

Table 5. Relative deviations in diameter measurement for 201.8 HBW 2.5 / 187.5 with manual vision measuring machine.

Light intensity (%)	Strategy	*s* (μm)	*d* (mm)	Δ*d* (μm)	Δd_{rel} (%)
1	IO	1.48	1.1062	-40.8	3.8
	OI	1.49	1.1060	-40.6	3.8
6	IO	0.99	1.1051	-39.7	3.7
	OI	2.38	1.1061	-40.7	3.8
10	IO	2.02	1.1051	-39.7	3.7
	OI	3.63	1.1045	-39.1	3.7

It is observed that the indentation diameter obtained for the reference block 201.8 HBW 2.5/187.5 is for all the cases higher than the certified value, with an average deviation of 3.75%.

Table 6. Relative deviations in diameter measurement for 499.5 HBW 5 / 750 with manual vision measuring machine.

Light intensity (%)	Strategy	*s* (μm)	*d* (mm)	Δ*d* (μm)	Δd_{rel} (%)
1	IO	0.97	1.3774	-7.9	0.6
	OI	0.82	1.3777	-8.2	0.6
6	IO	1.49	1.3767	-7.2	0.5
	OI	1.49	1.3770	-7.5	0.5
10	IO	1.16	1.3767	-7.2	0.5
	OI	1.40	1.3768	-7.3	0.5

It is verified that in both reference blocks, important deviations are obtained with respect to the certified value. Nevertheless, with this equipment no significant differences due to the intensity of illumination or the measurement strategy are appreciated.

It is observed that the relative deviations obtained for the hardness reference block 499.5 HBW 5/750 are close to the 0.5% value allowed by the standard but, as occurred with other instruments, the relative deviations obtained for the reference block 201.8 HBW 2.5/187.5 are too high, exceeding the admitted value [3].

3. Results and proposal for an alternative methodology

The experimental analysis carried out with the different optical instruments shows that the results obtained for the Brinell hardness measurements do not provide satisfactory results, reproducibility and precision with respect to certified values in one of the Brinell reference blocks.

After comparing the experimental measurements obtained with the different machines (Table I to Table VI) and taking into account their associated uncertainty, it is observed that these results are not compatible with the diameters and uncertainties given by the calibration certificate of the hardness standards.

It is verified that there is a high variability in the diameter measurements due to the different instrument used and the measurement parameters: magnification, type and intensity of illumination, measurement strategy, etc. The main reason is that the current definition of Brinell hardness [1] does not indicate a distinct geometrical edge that can be observed with optical equipment [6]. This means that depending on the instrument and the measurement parameters, measuring is done on a different pile-up or sink-in edge line, leading to a lack of reproducibility of the measurement as well as dispersion in the results obtained with different instruments, operators or laboratories [6].

Low et al. [6] proposes a new definition of Brinell hardness: *"The Brinell hardness indentation is defined, after the force is removed, as the surface area of the material under test that made contact with the ball indenter during the force application process".* This definition is based on the identification of a unique indentation edge: *"The edge of a Brinell hardness indentation is defined, after the force is removed, as the boundary of the surface area of the material under test that made contact with the ball indenter during the force application process, which is the point in any cross-sectional surface profile coplanar with the indentation axis at which the surface has its maximum rate of change of gradient when moving away from the center of the indentation".*

These new proposals based on direct physical measurement of indentation diameter rather than on optical observation were presented at the Working Group on Hardness (WGH) meeting in February 2015. The Working Group encouraged the continued research in hardness Brinell for the development of an international primary definition of the Brinell hardness scale [7].

Following these recommendations, works at the Universidad Politécnica de Madrid (UPM) were launched to determine the Brinell hardness value from three-dimensional scanning of the hardness indentation with a confocal microscope. With the developed measurement procedure [8] very good results have been obtained in the acquisition of the indentation points, reaching up to 99.9% of measured points, which allows the three-dimensional reconstruction of the Brinell indentation (Fig. 2 left).

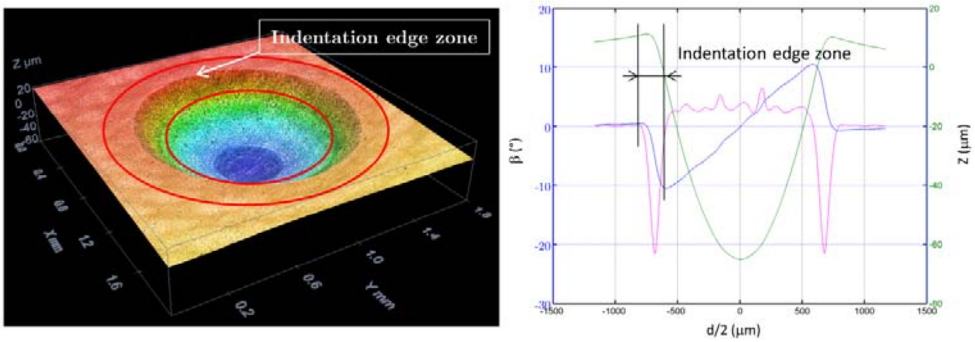

Fig. 2. *Brinell indentation edge zone.*

The model developed [8] is based on the coordinates (X, Y, Z) of the points explored with the confocal microscope and proposes to calculate the center of the Brinell indentation to define N cross sections coplanar with the central axis of the indentation. These sections, separated from each other by an angle θ, provide N central profiles on which their first and second derivatives can be determined.

Fig. 2 right shows the profile of a real indentation scanned with a confocal microscope (green), as well as the curves obtained when calculating the angle of the slope (β) (blue) and the second derivative of the profile (pink). A spline filter was applied to coordinates (X, Y, Z) to eliminate the high frequency component in the profiles, which allows us to neglect the roughness effect in the measurement and to reduce the noise in the derivative graphs.

Fig. 2 shows clearly that the edge zone of the indentation corresponds to a sudden drop in the slope angle, which results in a peak when calculating the second derivative of the profile. The location of the points at which the second derivative of the N profiles reaches a minimum (Fig. 3 left), defines the circumference of the edge and determines the Brinell hardness value from the diameter d of this circumference (Fig. 3 right).

This procedure is applied to measure the indentation diameter in the 499.5 HBW 5/750 standard. Measurements are repeated 4 times. The mean value is 1.36072 mm with a standard deviation of 0.51 μm and an estimated measurement uncertainty (k=2) de 2 μm .

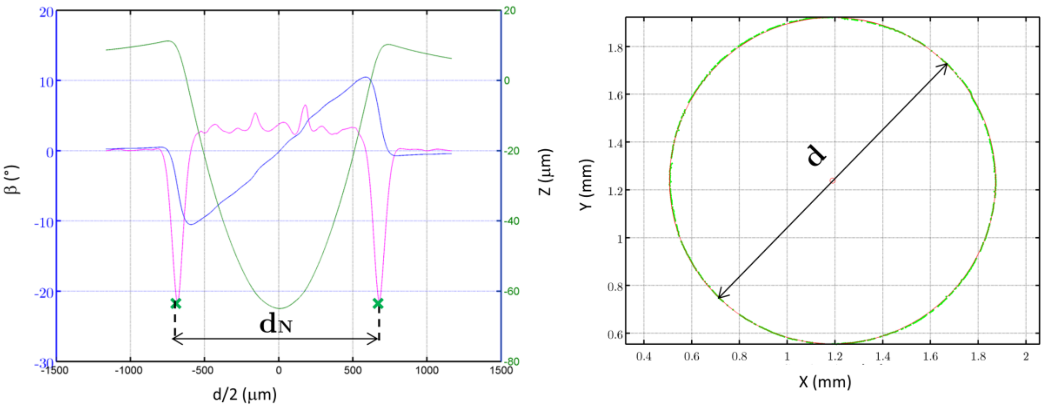

Fig. 3. Brinell diameter determination for an indentation profile N (left) and for a complete circumference of the edge (right).

4. Conclusions

Previous research and this experimental development have shown that the traditional Brinell hardness measurement methodology is simple and fast, but not enough to guarantee the reproducibility of measurements by different laboratories, mainly due to the lack of information about the edge line where measurements should be taken.

The model developed to determine the Brinell hardness based on the indentation measurement by confocal microscopy defines a unique indentation diameter on the edge point where the contact limit between the indenter and the material occurs during the hardness test. This point is characterized by a sudden change in the value of the curvature of the indentation edge and it is identified where the second derivative of a central profile coplanar with the axis of the indentation has its minimum value.

The diameter is calculated for the complete circumference of the edge, eliminating the effects of both the lack of axial symmetry of the indentation and the defects in the indentation surface.

This methodology, more complicated and slower than the traditional one, allows repeatability and reproducibility in the results, which are independent of the operator and the study section.

The model has been validated by synthetic data and by experimental ways on Brinell reference blocks certified with traceability to the International System. This validation demonstrates that calibration laboratories do not always measure at the point where the contact boundary between the indenter and the material occurs, complicating their repeatability and reproducibility. It is verified that the results obtained for the diameter by the developed models do not generally coincide with the certificates by the calibration laboratory because the measurement of the diameter is not performed in the same line of the indentation edge.

Measurements of the Brinell indentation using confocal microscopy allow the geometric characterization of the indentation surface and the detection of possible deficiencies in the Brinell test.

Measurement by confocal microscopy presents advantages in comparison with other existing proposals with mechanical contact equipment [5, 9, 10], because it does not produce physical contact with the surface, which avoids potential damage or marks on the test piece.

The studies supported the proposal of the Working Group on Hardness to state a physical definition of the Brinell indentation edge that allows the determination of a unique diameter on the curve that delimits the contact with the ball indenter during the force application process. The measurement procedure developed for the determination of the Brinell hardness by confocal microscopy is considered to be of great interest and highly useful for the calibration of Brinell reference blocks.

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