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DEVELOPMENT OF DEFINITION AND MEASUREMENT METHODOLOGY FOR HARDNESS INDENTATIONS OF BRINELL, VICKERS AND KNOOP

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Abstract:

This work investigates the definition and measurement of indentation size in Brinell, Vickers, and Knoop hardness testing. Since current standards require optical measurement without specifying a physical edge definition, optical results were compared with tactile measurements. Indentations were produced on steel, copper, and aluminum reference blocks using different hardness scales and loads. Tactile data were evaluated using a second derivative method and compared with optical measurements. The difference between methods was analyzed using a GLM. The hardness scale was the main source of systematic variability (41 %). Brinell measurements showed systematic underestimation by optical methods, whereas Vickers results exhibited negligible bias.

Keywords: Brinell; Vickers; Knoop; Definition; Edges; Diagonal measurement; Diameter measurement; illumination; focus plane

1. INTRODUCTION

Hardness testing is one of the most important methods for characterizing the properties of materials. The relevant standards for hardness testing, ISO 6506-1:2014 (Brinell) [1], ISO 6507-1:2023 (Vickers) [2] and ISO 4545-1:2023 (Knoop) [3], only describe that the size of the indentations produced must be measured optically. However, none of the corresponding standards specify where an indentation begins or ends. In the European project 22RPT01 TracInd BVK-H, one of the aims is to investigate how the diagonals or diameters of the indentations to be measured optically can be determined [4]. For this investigation, indentations were measured both optically and by tactile measurements and compared.

2. USED HARDNESS REFERENCE BLOCKS AND PROCEDURE

Hardness reference blocks made of steel, copper, and aluminum were used for the test. A steel block with a nominal hardness of approximately 150 HV was selected for measurements, along with a copper and an aluminum block. Indents were made on these blocks according to the Brinell method. These were produced with the conditions HBW 2.5/187.5, HBW 2.5/62.5 and HBW 2.5/31.25, which corresponds to a force-diameter index (see Eq 1) of 30, 10 and 5 respectively. Vickers indentations were also made. The HV 30, HV 1 and HV 0.2 methods were used. For the indentations applied using the Knoop method, the HK 2 and HK 0.2 methods were used.

$$\text{Force diameter index} = 0.102\,\frac{F}{D^2} \quad (1)$$

3. MATERIALS AND METHODS

3.1. Indentation Measurement Methodology

All indentations were measured using conventional optical methods, as is customary in hardness measurement technology. A Nikon MM800 measuring microscope with a numerical aperture (NA) of 0.45 was used, i.e., corresponding to a maximum measurable slope of 26.7°. The specimen was moved under the objective lens so that each edge of the indentations was within the field of view. Hardness indents less than 150 µm in length were analyzed by a camera, by taking a photo of the indentation and measuring the distance between the edges using diagonal measurement and pixel counting. An Axioskop microscope from

Zeiss and the corresponding AxioCam ICC 5 camera were used for the procedure. After the optical determination of the indentation size, all indentations were scanned using a Tecncor P 17. To save time, the entire indentation was not scanned, but only the partial area of approximately 10 %. The measurement was focused on the region of interest for the diagonal or diameter measurement. The scan resolution in scan direction was 0,4 µm. The distance between to scan lines are made every 1 µm.

3.2. Determination of the diameter according to the largest gradient

Based on the study reported by Li Ma et al. [5], this work investigates the relationship between the maximum gradient of the tactile measurement curve and the indentation size quantified through optical measurements. To this end, the three-dimensional data acquired from the tactile measurement were processed by manually defining a range on each side of the indentation. This selection restricted the search for the minimum to a region corresponding to the indentation edge, as shown in Fig. 1.

The tactile data was arranged on a rectangular grid of points x and y, with a height value $z(x, y)$ assigned to each point. The data were linearized line by line, by using piecewise linearization, with a window of 11 points. This linearization was necessary to reduce measurement noise that would affect the calculation of the first and second derivatives. The first derivative was obtained from the slope of the linear fit, while the second derivative was obtained by calculating the change in slope between adjacent points. The slope was converted to angle to determine the point at which it corresponds to the optical numerical aperture angle. An example of the data for one line is shown in Fig. 2.

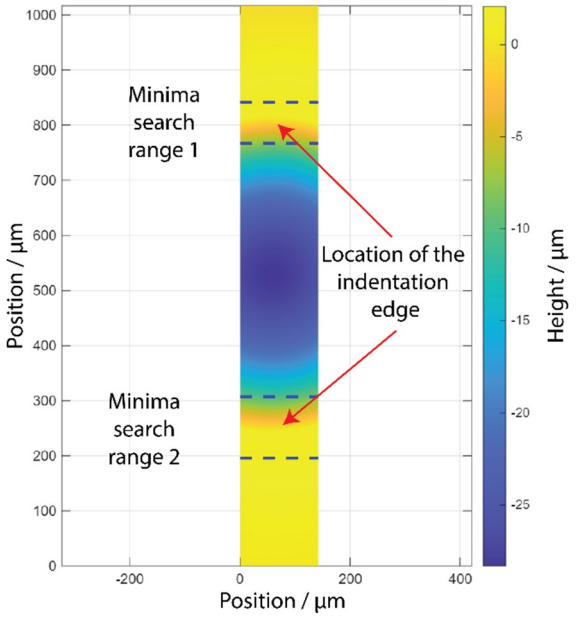

Figure 1: Pseudo-color map of measured profiles of a Brinell indentation. Minima search range selection on an indentation tactile measurement. The blue dashed lines indicate the boundaries of the search range for the minimum in the second derivative and were placed conservatively to account for indentation edge movement between different lines.

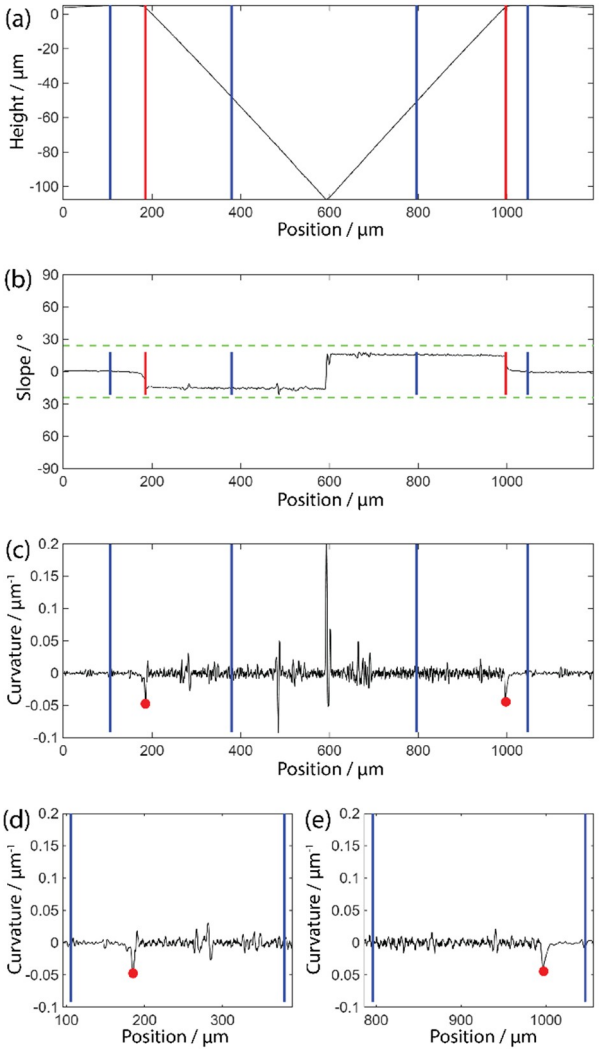

Figure 2: Procedure for finding the minimum in the second derivative on a line of a Vickers indentation. (a) Linearized data, (b) first derivative converted to angle, (c) second derivative, and (d,e) zoomed view of the search ranges on the second derivative. The blue vertical lines indicate the search range, while the red lines and the red dots indicate the location of the minimum in the second derivative. The green line indicates the angle corresponding to the NA of the optic used, 26.7°.

The minima point coordinates in the second derivative within the search ranges were collected for each line and used to determine the size of the indentation. This was compared with the optical measurements by calculating the difference, as shown in Eq. 2.

$$\Delta d = d_{optical} - d_{tactile} \quad (2)$$

3.3. NA point calculation

The first derivative data was used to determine whether the slope of the indentation matched the angle associated with the acceptance half angle of the optic. The calculation was performed by checking the first instance, from the outside of the indentation inward, in which the slope passes from an angle smaller than 26.7° to an angle greater than 26.7°. If that occurred, the coordinates of such point were stored. The angle α of 26.7° corresponds to acceptance half angle of the optics used in the measuring microscope. According to Eq. 3, the optics used have an NA of 0.45. The refractive index n is set as 1 in microscopic systems at the transition from glass to air.

$$\boldsymbol{NA = n \sin\alpha} \quad (3)$$

3.4. Analysis of the data

The statistical analysis was performed using an analysis of variance framework based on the general linear model (GLM). The response variable was the difference Δd. The fixed factors considered in the initial model were hardness scale (HBW, HV), load (expressed in kgf), and the hardness block material (Al, Cu, Steel). All pairwise interaction terms were included as possible factors. Because the applied load is specific to each hardness scale, it was treated as a factor nested within the hardness scale. This nesting reflects the experimental structure, as the load levels are not shared across scales and therefore cannot be interpreted independently of the corresponding scale. Model selection was carried out using a stepwise procedure without hierarchy constraints with alpha-to-enter and alpha-to-remove parameters both set to 15 %. [6]

4. RESULTS AND DISCUSSION

4.1. Analysis of the data for the second derivative method

The ANOVA (Analysis of variance) results, summarized in Table 1, indicate that there is a statistically significant effect on the difference between tactile and optical measurements of the indentation size due to the material, the hardness scale and their interaction. The hardness scale had the highest statistical significance, as shown in the interaction plot in Figure 3.

For the Brinell test, the indentation diameter was systematically underestimated by the optical method relative to the tactile measurement, with an average of -6.7 µm. In contrast, for the Vickers test, the mean difference between methods was close to zero, with an average of -0.3 µm. This behavior explains the dominant effect of the hardness scale in the model. A plausible explanation is related to the geometrical characteristics of the indentations. The Vickers indenter produces recognizable corners that can be more reliably identified, whereas the circular Brinell indentation is more susceptible to ambiguity at the boundary due to material pile-up [7]. The material also affected the average difference, with the Cu specimen for the Brinell test having the largest mean difference. This also explains the significance of the material detected in the ANOVA. The interaction between material and hardness scale was weakly significant.

Table 1: Analysis of variance for the difference between tactile and optical measurements.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	2	85.74	42.87	3.45	0.045
Hardness scale	1	367.55	367.55	29.59	0.000
Material × Hardness scale	2	68.41	34.20	2.75	0.080
Error	30	372.65	12.42		
Lack of fit	12	129.57	10.80	0.80	0.647
Pure error	18	243.08	13.50		
Total	35	894.34			

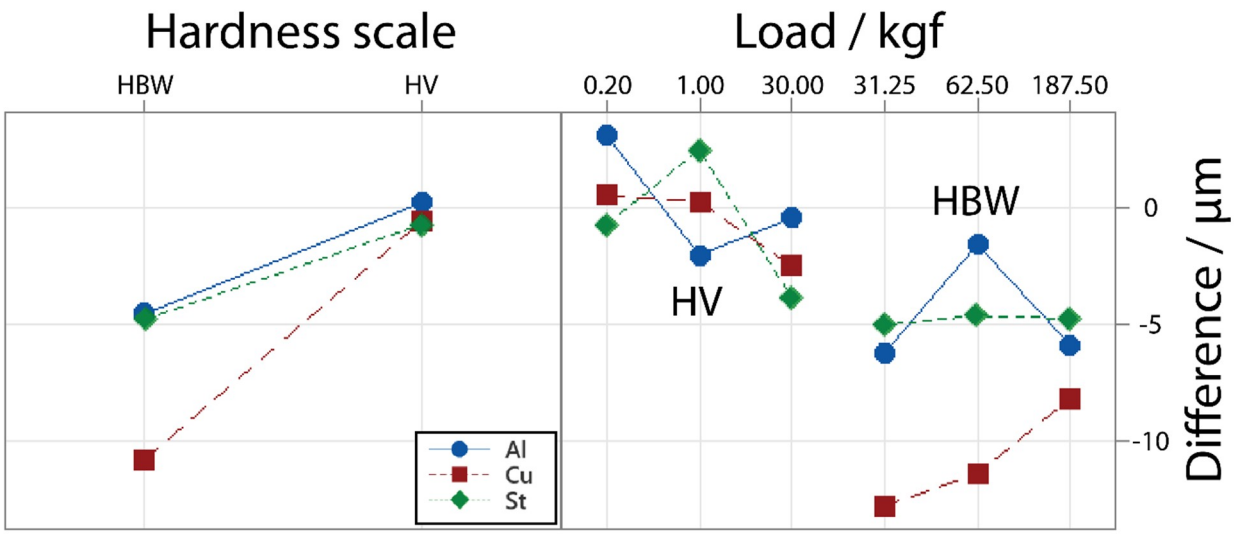

Figure 3: Interaction plots of the difference between tactile and optical measurements as a function of hardness scale (HBW, HV) and applied load (kgf), for the three materials (Al, Cu, Steel). The left panel shows the effect of hardness scale, while the right panel shows the effect of load nested within each scale.

The applied load was excluded during the stepwise ANOVA procedure. This is likely because the effect of load on the measurement difference is nested within the hardness scale, so the hardness scale factor alone captures the main effect. The Knoop indentations were also excluded from the analysis since the tactile measurement could not provide adequate results for the analysis with the largest gradient method. It is not possible to place the scan line in such a way that it passes through both peaks of the indentation. Therefore, it makes no sense to evaluate the indentation edges.

Considering the adjusted sum of squares, the hardness scale accounts for approximately 41 % of the total variability. This contribution is comparable to the residual error, about 42 %, and substantially larger than the contributions attributed to material, about 10 %, and the interaction between the material and the hardness scale, about 8 %. These results indicate that the measurement difference between tactile and optical methods is primarily governed by the hardness scale, with a comparable portion of variability remaining unexplained by the model.

4.2. Analysis of the data for NA angle method

The NA method yielded valid edge detection only for a subset of indentations, like in the example of Fig. 4, for the Al specimen. Specifically, this occurred only for the Brinell indentations with a load of 187.5 kgf. The average difference between the diameter measured by the NA measurement and the tactile measurement was -4.2 µm, a result similar to the deviation of the optical method from the tactile method.

5. SUMMARY

The study addresses the lack of a physically defined indentation edge in current Brinell, Vickers, and Knoop hardness standards, where optical measurement is required but the edge position is not explicitly specified. Indentations were produced on steel, copper, and aluminum reference blocks using different hardness scales and loads. Optical measurements were compared with tactile measurements processed through a second derivative method and an NA method related to the numerical aperture. The difference between optical and tactile indentation size was analyzed using a

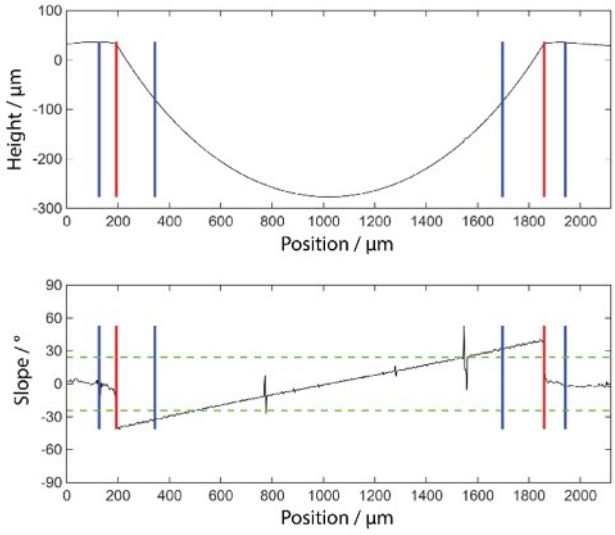

Figure 4: Height and slope of a line of data from the Brinell 187.5 kgf indentation on Al. The slope starts around 0° outside the impression and crosses the NA angle value (green lines) in proximity to where the curvature method detects the edge.

general linear model including hardness scale, material, and load nested within hardness scale. The main findings are:

1. The hardness scale was identified as the dominant source of systematic variability, accounting for approximately 41 % of the total variance, while the residual component accounted for about 42 %. Material and its interaction with hardness scale contributed to smaller portions of variability.
2. Brinell measurements showed a systematic overestimation of indentation size by the tactile measurement, whereas Vickers measurements exhibited negligible bias.
3. The NA method produces results comparable to the second derivative method, but only applies when the indentation is large enough to meet the angle threshold. This is given by indents with a force diameter index of 30.

ACKNOWLEDGMENT

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REFERENCES

[1] International Organization for Standardization, ISO 6506-1:2014 Metallic materials - Brinell hardness test - Part 1: Test method, (2014).

[2] International Organization for Standardization, ISO 6507-1:2023 Metallic materials - Vickers hardness test - Part 1: Test method, (2023).

[3] International Organization for Standardization, ISO 4545-1:2023 Metallic materials – Knoop hardness test - Part 1: Test method, (2023).

[4] C. Kuzu, A. Germak, F. Menelao, A. Štibler, G. Genta, M. Loewit, J. Borovský, G. Maculotti, M. Hiti, A. Prato, E. Pelit, J. Fidelus, T. Apostol, Š. Ališić, B. Fakić, P. Reinstädt, F. Turotti, R. Affri, B. Muminovic, A. Alić, Traceability for indentation measurements in Brinell-Vickers-Knoop hardness, Measurement: Sensors 38 (2025) 101453. https://doi.org/10.1016/j.measen.2024.101453.

[5] L. Ma, S. Low, J. Song, An approach to determining the Brinell hardness indentation diameter based on contact position, in: ACTA IMEKO, 2014: p. 9.

[6] D.C. Montgomery, G.C. Runger, N.F. Hubele, Engineering Statistics, 5th ed., Wiley, 2010.

[7] K. Herrmann, ed., Hardness Testing: Principles and Applications, ASM International, 2011.