

INVESTIGATION OF BRINELL INDENTATION DIAMETER FROM CONFOCAL MICROSCOPE MEASUREMENT AND FEA MODELING

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Abstract – Significant measurement differences have been continually observed worldwide in Brinell hardness tests, even in the secondary calibration laboratories that calibrate test block reference standards. The main cause of this problem is the edge of the indentation is not a distinct boundary, but is instead a curved surface from either material piling up (pile-up) or sinking in (sink-in) caused by plastic flow of the material surrounding the ball indenter. This makes it difficult to clearly resolve the edge of the indentation and thus determine the indentation diameter. In this research, Brinell hardness indentations were made using various indentation forces and ball indenter sizes. Using a confocal microscope, the indentations were measured in three dimensions from which the indentation profiles were determined. Additionally, finite element analysis (FEA) models were developed for studying the location of contact points at indentation pile-up edges. From both microscope measurements and FEA simulations, the difference between the measured indentation diameter and the actual contact diameter was determined for each indentation.

Keywords: Brinell hardness, Finite Element Analysis (FEA), pile-up

1. INTRODUCTION

Brinell hardness, which was proposed by J. A. Brinell in 1900 [1], is an important and popular test method used in industry for quality control and acceptance testing of metallic materials and products. The Brinell hardness test involves indentation of the test material in a specific way using various sizes of tungsten-carbide (WC) ball indenters. After the removal of the indentation force, the diameter of the indentation is measured using an optical measuring microscope or an optical automatic image analyzing system [1, 2]. Although the Brinell hardness test has been widely used by industry for more than 100 years, significant measurement differences have been continually observed worldwide, even in the secondary calibration laboratories that calibrate test block reference standards. The main cause of this problem is the measurement of the indentation diameter in which the location of the edge must be clearly determined. In most cases, the edge of the indentation is not a distinct boundary, but is instead a curved surface with

either material pile-up or sink-in, due to the plastic flow of the material surrounding the ball indenter.

An early experimental study of surface deformation around a spherical indenter found that the amount of pile-up and sink-in is related to the strain-hardening exponent of the materials [3] and was ultimately expressed as a functional relationship [4]. With the advantage of computational methods, it was determined from finite element analysis (FEA) modeling that the pile-up/sink-in is not only related to strain hardening [5, 6], but also related to yield strain (the ratio of yield strength Y to elastic modulus E) and indentation ratio (indentation depth h over indenter radius R) [7, 8].

In industry, Brinell hardness indentations are measured using optical measuring microscopes by observing the dark-to-light transition at the indentation edge. Measuring instruments can vary from simple hand-held microscopes with a 20× to 40× magnification to common bench-type microscopes having multiple lenses. It has been demonstrated that the diameter measurement of a Brinell indentation can be highly dependent on the numerical aperture (NA) of the lens and the curvature of the material at the indentation edge [9]. Lenses having a different NA or magnification may view light reflected off of the curved indentation edge at differing angles causing the dark-to-light transition area to appear differently at varying locations.

Ideally, a Brinell hardness measurement should be based on the actual contact area of the ball indenter with the test material. However, for a typical Brinell hardness test, the optical measurement of the indentation diameter is usually not equal to a diameter measurement based on only the contact area. The focus of our study was to examine the differences between the optical measurement of a Brinell hardness indentation diameter and the diameter based on the indentation contact area.

The differences are caused by several factors including material deformation at the indentation edge related to material properties, ball indenter size and indentation force. To study these effects, Brinell hardness indentations were made in three typical hardness reference test blocks of different hardness levels that produced different ratios of pile-up to indentation depth. The indentations were made using various indentation forces and ball indenter sizes.

The location of the indentation contact point at the curved edge area was determined from finite element

analysis (FEA) models and indentation profiles obtained from confocal microscope measurements. Comparing this information with the real Brinell hardness measurement values, the deviation of the measured diameter from the contact diameter can be determined for each indentation.

2. BRINELL HARDNESS TEST AND MEASUREMENT

The Brinell hardness tests were made by a commercial laboratory in accordance with ASTM E10 [2] using a commercial standardizing Brinell hardness machine. The nominal Brinell hardness values for the three reference blocks were 259 HBW 10/3000, 385 HBW 10/3000, and 497 HBW 10/3000. Four different standard sizes of tungsten carbide ball indenters were selected with diameters of 1 mm, 2.5 mm, 5 mm and 10 mm. Various standard indentation forces were applied for each size of ball indenter, as shown in Table 1. Fig. 1 is a photograph of one of the reference blocks showing the indentations made with the varying ball sizes and applied forces. The indentation diameters were measured automatically using an image analysing system by a commercial laboratory with a reported expanded uncertainty of better than $\pm 3 \mu\text{m}$ with a confidence level of 95 %.

The Brinell hardness number, HBW , can be calculated from the measured mean diameter of the indentation [2] as:

$$HBW = \frac{2F_{kgf}}{\pi D(D - \sqrt{D^2 - d^2})} \quad (1)$$

where F_{kgf} is the indentation force in kgf^* , D is the diameter of the ball indenter in mm, and d is the measured mean diameter of the indentation in mm.

Table 1. Indenter ball size, testing force and force-diameter ratio used to produce the Brinell hardness indentations

Indentation No.	Ball diameter, D (mm)	Indentation force, F		Force-diameter ratio, F/D^2 (kgf/mm^2)
		(N)	(kgf^*)	
1	10	29420	3000	30
2	10	24517	2500	25
3	10	19613	2000	20
4	10	14710	1500	15
5	10	9807	1000	10
6	10	7355	750	7.5
7	5	19613	2000	80
8	5	14710	1500	60
9	5	9807	1000	40
10	5	7355	750	30
11	5	4903	500	20
12	5	2452	250	10
13	2.5	2452	250	40
14	2.5	1839	187.5	30
15	2.5	612.9	62.5	10
16	1	1839	187.5	187.5
17	1	612.9	62.5	62.5
18	1	306.5	31.25	31.25

*Kilogram-force (kgf) units are included because of historical use by ASTM [2].



Fig. 1. The indentations made with varying ball sizes and loads

3. CONFOCAL MICROSCOPE MEASUREMENT

In order to determine the actual contact diameter, it was necessary to obtain the cross-sectional profile of the indentation. This was accomplished using a confocal microscope to first measure the three-dimensional topography of the indentation. A $20\times$ objective was used, providing a square $0.8 \text{ mm} \times 0.8 \text{ mm}$ field-of-view. The image was captured as 512×512 pixels. Therefore, the nominal pixel size was $1.5625 \mu\text{m} \times 1.5625 \mu\text{m}$. For indentation sizes larger than 0.8 mm , the topography images consisted of several images stitched into one large image using the commercial stitching software of the instrument. For the $20\times$ objective, the maximum surface slope that can be captured was 30° . For some indentations, the indentation edge had surface slope angles steeper than 30° and could not be measured. These were typically the indentations having large force-diameter ratios as defined in Table 1.

3.1. Calibration and quality control

Several aspects of the confocal microscope calibration were verified by measuring several types of calibration and check standards. These included:

- A smooth, flat reference standard for eliminating any wavefront distortion of the microscope and for checking the vertical resolution limit for measuring roughness. The procedure for eliminating wavefront distortion is a standard procedure from the manufacturer. The root mean square (rms) roughness of the sample is less than 1 nm .
- A calibrated step height of $10.5 \mu\text{m}$ check standard for checking the overall z-scale calibration of the microscope.
- A sinusoidal roughness standard, NIST Standard Reference Material (SRM) 2073a, having an arithmetic mean roughness, R_a , equal to $2.97 \mu\text{m}$, and a spatial period of about $100 \mu\text{m}$, for testing the accuracy of the microscope for x-measurements.

All verifications were performed each day that the instrument was used.

3.2. Indentation profile obtained from confocal microscope measurements

Three-dimensional topography of each indentation was captured from the confocal microscope and output as ASCII format data. The estimated statistical standard uncertainty is $3 \mu\text{m}$ ($k=2$). An indentation profile was then calculated from

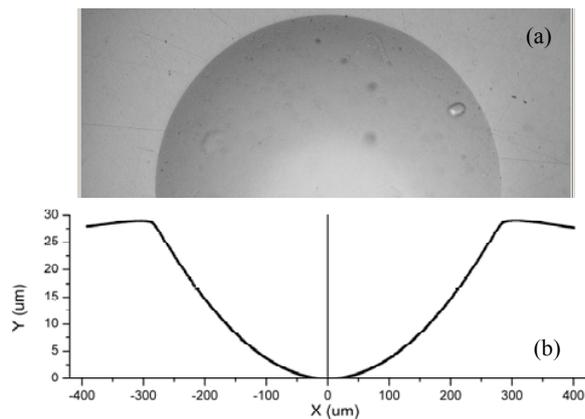


Fig. 2. (a) The indentation image and (b) its corresponding cross-sectional profile in the x direction obtained from three dimensional topography measurement of an indentation made in the 259 HBW 10/3000 block using a 2.5 mm diameter ball and 612.9 N (62.5 kgf) indentation force

the three-dimensional data. Because the test surfaces of the reference blocks were not perfectly perpendicular to the normal axis of the microscope, the resulting three-dimensional indentation topography had to be leveled by mathematical data processing. Once leveled, multiple cross-sectional profiles were calculated across the central portion of the indentation. The profile having the largest fitted radius was determined to be the indentation cross-sectional profile analogous to where the diameter would be measured in industry by an optical measuring microscope. Fig. 2 shows the indentation image from the confocal microscope and its corresponding cross-sectional profile in the x direction of an indentation made in the 259 HBW 10/3000 block using a 2.5 mm diameter ball and 612.9 N (62.5 kgf) indentation force.

4. FINITE ELEMENT MODELING

The commercial FEA software, ABAQUS[†], was used for modeling the Brinell indentations. The elastic-plastic properties of the reference blocks were obtained from uniaxial tension tests of reference block material having similar Brinell hardness levels. Taking advantage of axis-symmetry of both the ball indenter and the test specimen, only a cross section of a ball was modeled. A rigid curved plate with the same radius of the ball indenter having 30° of arc length was added on the top of the cross-section of the ball indenter to evenly distribute the concentrated force applied to the curved plate. The modeled specimen width was over ten times the indentation radius, and the height was over 30 times the indentation depth to eliminate any boundary effects. The minimum element size of the specimen was 1.6 μm for the smaller indentations, and 3 μm for the larger

[†] Certain commercial equipment, instruments, materials or companies are identified in this paper to specify adequately the experimental and computational procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

indentations, which is compatible to the confocal microscope x and y resolution of 1.56 μm .

5. RESULTS AND DISCUSSIONS

5.1. Indentation edge contact point from FEA modeling

Theoretically, the Brinell hardness value should be the ratio of the indentation force to the surface area of indentation. According to Brinell hardness test method standards, the surface area of indentation is determined by measuring the diameter d of the resulting indentation after removal of the indentation force [2]. Ideally, the surface area should be the contact area while under the indentation force. As in-situ measurement of indentation diameter is not possible, the diameter is measured after removing the indenter and the indentation force. However, the indentation shape changes after removing the indentation force primarily because of the elastic recovery of the test material.

From FEA modeling, the indentation edge contact point was determined for the condition when the indentation process is under the full indentation force. The corresponding mesh-node coordinate was then identified. The FEA modeling process was continued until the indentation force was removed. By tracking the node coordinate, the position of the indentation edge contact point was determined for the condition when the force is removed. Fig. 3 shows the FEA mesh geometry for a 1 mm diameter indenter ball indenting a 259 HBW 10/3000 material (Fig.

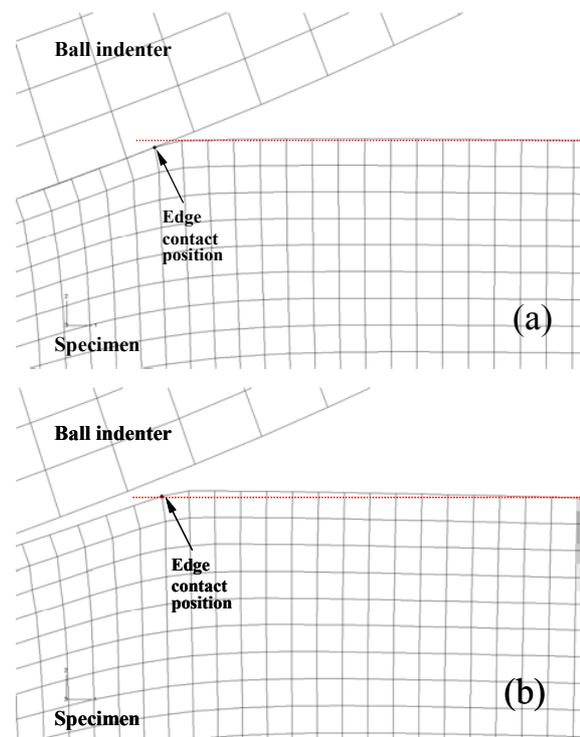


Fig. 3. FEA mesh geometry for a 1 mm diameter ball indenting a 259 HBW 10/3000 material: (a) under an indentation force of 306.5 N (31.25 kgf), and (b) after removal of the indenter and the indentation force. The arrow indicates edge contact mesh node point

3a) under a indentation force of 306.5 N (31.25 kgf), and (Fig. 3b) after removal of the indentation force. It can be seen that the top surface is almost flat under the full indentation force and piles up after removing the indentation force. This depends on strain hardening of the indented material and the indentation depth, etc. [5-8]. In addition, the edge contact position while under the indentation force (see Fig. 3a) and after removing the indentation force (see Fig. 3b) are not at the apparent edge of the indentation.

5.2. Comparison of indentation edge contact point and optical measurement point.

To examine the differences between the optical measurement of a Brinell hardness indentation as measured in industry and the actual diameter of the indentation contact area, we needed to combine the information obtained from the FEA modeling and the optical measuring microscope into a common reference frame. To do this, we determined the locations of the edge contact point from the FEA modeling and the optical measurement point from the measuring microscope on a single indentation profile obtained from the confocal microscope. A basis for determining the contact point location on the measured indentation profile had to be devised because the FEA indentation data does not exactly model the measured profile. Examination of the FEA indentation models showed that, in each case the indentation edge contact boundary appeared to occur at the starting point of where the slope of the indentation had its greatest change. This was clearly illustrated by calculating the slope angle from point to point on the indentation profile, α_s , as,

$$\alpha_s = \tan^{-1}(dy/dx) \quad (2)$$

where dx and dy are data spacing in x and y direction.

Fig. 4a shows the right half of a FEA generated indentation profile with the increasing radius in the positive x direction and the indentation center at $x = 0$. A vertical dashed line indicates the indentation edge contact position. Fig. 4b shows the slope angles of the same indentation profile plotted on the same x -axis scale. A magnified view

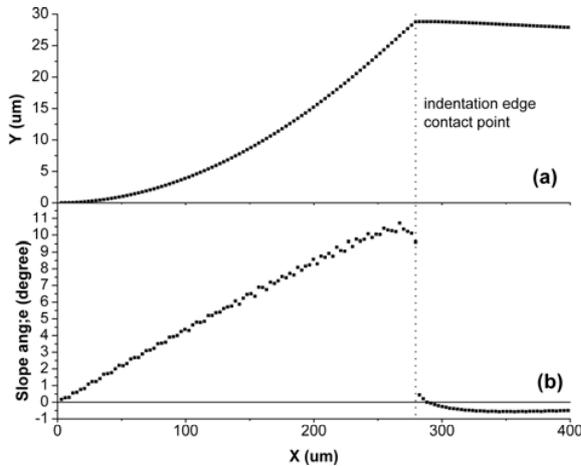


Fig. 4. The indentation profile (a) and its corresponding slope angle profile (b) from FEA modeling. The vertical dashed line indicates the indentation edge contact position

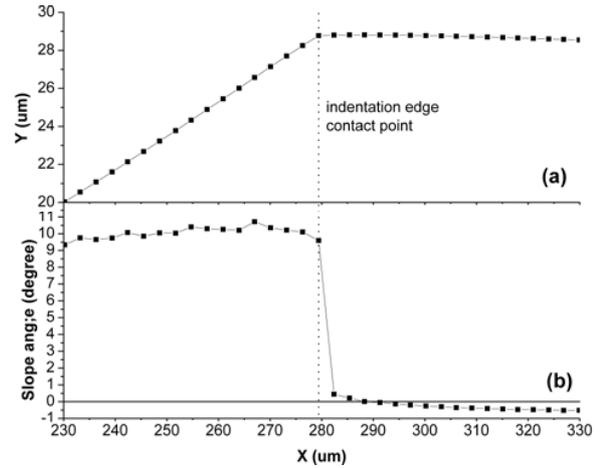


Fig. 5. The magnified view of the edge area of the indentation profile (a) and its corresponding slope angle profile (b) from FEA modeling. The vertical dotted line indicates the indentation edge contact position

of the edge area of the same indentation is shown in Fig 5a and the corresponding slope angle plot is shown in Fig. 5b. It can be seen that the edge contact point occurs at the start point of the sudden drop in slope angle.

Assuming that this is a characteristic of the real Brinell hardness indentations examined in this study, this behavior was then applied to the indentation profile obtained from the confocal microscope measurements. This is demonstrated in Fig. 6b for an indentation made in the 259 HBW 10/3000 block using a 2.5 mm diameter ball and 612.9 N (62.5 kgf) force. The indentation contact location was chosen at the point where the slope angle drop occurs, indicated by the vertical dashed line. The corresponding location on the measured indentation profile is shown in Fig. 6a.

The location at the indentation edge that was selected for

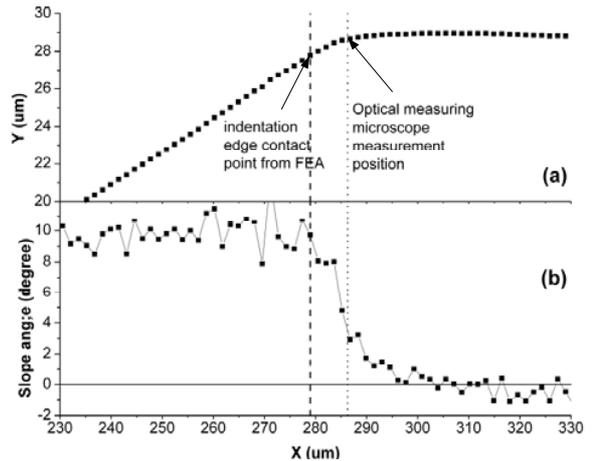


Fig. 6. The magnified view of the edge area of the indentation profile (a) and its corresponding slope angle profile (b) obtained from confocal microscope measurement for the indentation in the 259 HBW 10/3000 block using a 2.5 mm diameter ball and 612.9 N (62.5 kgf) indentation force. The dashed and dotted lines indicate the indentation contact position and optical microscope measurement position, respectively

the measurement of the indentation diameter using the optical measuring system can be determined from the actual measured diameter value. This location is also indicated in Fig. 6, illustrating that the indentation contact point and the location selected for the indentation diameter measurement are not the same. The optical measuring microscope measured the indentation radius to be $7.3 \mu\text{m}$ larger than the actual contact radius, corresponding to a 12 HBW difference.

5.3. Defining the edge of a Brinell indentation

Fig. 7 shows three indentation profiles measured with the confocal microscope (Fig. 7a) and their corresponding slope angle profiles (Fig. 7b). The indentations were made using three different combinations of ball-size and force providing the same force-diameter ratio of 30 (see Table 1): 10 mm ball and 29.42 kN (3000 kgf); 5 mm ball and 7.355 kN (750 kgf); 2.5 mm ball and 1.839 kN (187.5 kgf). It can be seen from Fig. 7b that the slope angles outside the indentation and in the pile-up area are quite similar, around 2.5° . However, the maximum slope angle, which occurs at the edge of the indentation, decreases from 20° to 16° as the ball diameter increases from 2.5 mm to 10 mm.

The measurement position from the optical measuring microscope for each indentation profile is indicated as a

dotted line in both Fig. 7a and Fig. 7b, and additionally with an arrow in Fig. 7b. From Fig. 7b, it can be seen that all of the optical measurement positions occurred in the lower area of the rapid slope angle drop at nearly the same slope angle of about 2° to 3° (see the arrows in Fig. 7b). This slope angle is likely to be dependent on the optics of the specific microscope measuring system. Other measuring systems may interpret the indentation edge at a different slope angle resulting in a different value to be measured for the indentation diameter.

6. CONCLUSIONS

The Brinell indentation diameter was investigated from optical and confocal microscope measurements of actual indentations, as well as from finite element modeling of indentations. The indentation edge contact position, while under the indentation force and after removing the indentation force, was determined from the FEA modeling.

The edge of an indentation is the area of interest for measuring the indentation and calculating the hardness value. It has been demonstrated that the surface of the indentation edge is an area of rapidly changing slope angle. From the slope angle profile of the indentation cross-section, the real contact position has been shown to be at the

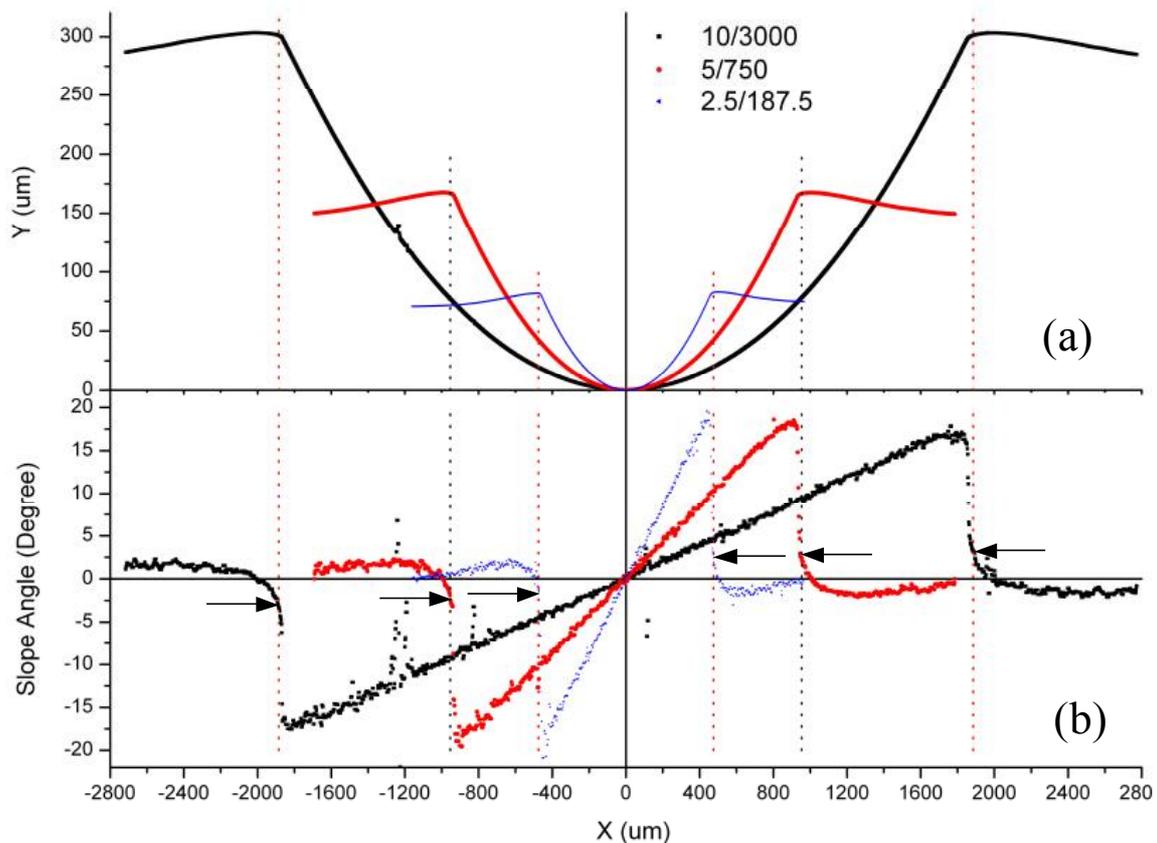


Fig. 7. Indentation profiles (a) and their corresponding slope angle profiles (b) from confocal microscope measurements for the same force-diameter ratio of 30. The dotted and straight lines indicate the optical measurement positions

beginning of the sudden slope drop close to the maximum slope angle. However, the experimental measurement using the optical measuring system chose the indentation edge close to the end of slope drop between 2° to 3°, which is likely dependent on the microscope.

The edge of a Brinell hardness indentation is usually not a well-defined delineation between the indented and surrounding material, and accordingly does not provide an unambiguous boundary for measuring the indentation diameter. In reality, it is a curved surface that reflects light in such a way that a microscope image sees a zone transitioning from dark to light. As a result, there is no accepted objective definition for the edge of the indentation. This study indicates that it may be reasonable to define the edge of a Brinell hardness indentation based on the slope angle of the surface of the indentation edge.

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