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Proposed definition for the Brinell hardness indentation edge

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ABSTRACT
The industrial Brinell hardness test has been in common use for over 100 years. The test is defined by standardized procedures stating that the Brinell hardness value is proportional to the test force divided by the surface area of the indentation. The test procedures require that the surface area be determined by measuring the indentation diameter after removing the test force. This measurement is usually made using an optical microscope, but without having a physical definition of the indentation edge. This paper proposes a physical definition of the indentation edge such that the Brinell indentation diameter can be unambiguously measured.

Section: RESEARCH PAPER

Keywords: Brinell; contact; diameter; hardness; indentation

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1. INTRODUCTION

Brinell hardness is an indentation test that has been in common usage by industry for well over 100 years. It is a simple test in concept in which a spherical ball indenter is forced under a specified test force into the test material, causing permanent indentation in the material. The Brinell hardness value (HBW) is proportional to the test force divided by the surface area of the indentation. International test methods [1],[2] specify that the indentation surface area be determined based on the applied test force, the diameter of the ball indenter and by measuring the diameter of the indentation after the test force and indenter are removed. Typically, the diameter measurement is made using an optical microscope measuring system.

For most users of Brinell hardness, the test procedure is indeed simple, providing a Brinell hardness value with reasonable uncertainty levels for their needs in spite of the common use of very low-magnification microscopes to measure the indentation diameter. This is acceptable since many product specifications that require the Brinell hardness test to determine compliance, often specify large ranges of acceptable values or simply specify maximum or minimum limits on the hardness value.

For laboratories that calibrate Brinell hardness reference blocks, as well as the Primary National Metrology Institutes, the uncertainty in the hardness measurement needs to be minimized since they are at the first levels of the traceability chain in these measurements.

It is well recognized that Brinell hardness measurement accuracy is primarily related to measurement of the indentation diameter [3]. There are two main reasons for the significant contribution of error from the diameter measurement. The first is because of the many factors that influence a length measurement when using an optical microscope. The second reason is that the edge of a metallic indentation is curved and without a distinct physical edge that can be definitively observed with an optical microscope. This second reason is complicated by there not being an accepted physical definition of the edge of a Brinell indentation. This paper proposes such a definition that has been demonstrated to be measurable.

In section 2 we discuss the Brinell hardness test procedure. Section 3 discusses two choices of defining the indentation edge; either by a practical definition based on defining an optical measuring system or a physical definition based on a direct measurement of the indentation. In the next two sections, we describe our work in modeling Brinell indentation and our experimental measurements of actual Brinell indentations. In section 6 we compare Brinell hardness measurements made using our technique with typical industrial measurements. Finally, in the concluding section we propose physical definitions for the edge of a Brinell hardness indentation and the Brinell indentation itself.

2. BRINELL HARDNESS TEST PROCEDURE

Brinell hardness, as it is specified today, is measured by indenting a material normal to its surface with a hardmetal ball. A specified force is applied to the ball; the force is maintained for a specified time; the force is removed; and the surface area of the resulting indentation is determined, most often by optically measuring the diameter of its projected area. The Brinell hardness value is calculated based on the applied force divided by the indentation surface area as:

$$HBW = Constant \times \frac{Test\ Force}{Surface\ area\ of\ indentation} \qquad (1)$$

$$HBW = 0.102 \times \frac{2F}{\pi D\left(D - \sqrt{D^2 - d^2}\right)} \qquad (2)$$

where F = test force (N)
D = diameter of the ball indenter (mm)
d = diameter of indentation (mm).

From an idealistic point of view, it may be preferable to define the test as: a specified force is applied to a nondeformable ball; the force is maintained until the plastic flow of the indented material under load ceases; and then the contact surface area between the ball and test material is determined while under load. As suggested by Meyer [4], it may also have been more appropriate to calculate a hardness value as a mean pressure based on the applied force divided by the projected contact surface area under load. This value, which increases with load, better represents the ball indentation behavior of a material where the resistance to penetration increases with increasing applied force.

Clearly this idealistic test procedure would not have been practical for general industrial use. Brinell approximated the nondeformable ball by using a hardened steel ball which has now been replaced with a hardmetal (tungsten carbide) ball. Brinell found that plastic flow was most rapid in the first 30 s of applying the maximum load, leading to his recommendation for a 30 s time application, now shortened to between 10 s and 15 s. More importantly, there was, and continues to be, no practical technique to measure the contact surface area while under load, due to the generally opaque nature of both indenter and test material (in recent years, methods for area measurement of transparent test materials under load have been investigated [5], as have measurements using transparent indenters [6]). Brinell wanted a test that gives a constant value independent of load and found that basing the hardness value on the indentation surface area better exhibited this behavior as compared to the projected area [7]. The test procedure developed by Brinell determines the contact surface area after removing the indenter and force by measuring the diameter of the projected area of the indentation and assuming that the unloaded indentation retains the shape of the ball indenter (a generally valid assumption considering the plastic deformation characteristics of most metals).

The above discussion is given to point out that the Brinell hardness test procedure is not a measurement of a physical property of a material. Brinell hardness is an ordinal quantity prescribed by a test method procedure combining simultaneous and sequential measurements of force, length and time. The test was developed to provide industrial manufacturers with a tool to correlate a simple test result to a desired material property, such as strength or wearability. Keeping this in mind, it is more appropriate to base a definition of Brinell hardness on the Brinell hardness test procedure rather than an ideal property measurement.

3. DEFINING THE INDENTATION EDGE

One role of the Working Group on Hardness of the Consultative Committee on Mass and Related Quantities (CCM-WGH) of the International Committee for Weights and Measures (CIPM) is to develop definitions of the hardness tests for use by the world's National Metrology Institutes (NMIs). This includes the Brinell hardness test. In November 2003, the CCM-WGH initiated a CCM Brinell hardness key comparison (KC) [CCM.H-K2] between the world's NMIs that standardize Brinell hardness. The KC concluded in 2004, and, in 2005, Hattori (National Metrology Institute of Japan) presented the initial results of the CCM.H-K2 Brinell hardness key comparison [8] to the CCM-WGH members.

Two of the conclusions from the analysis of the KC data were:

- The difference between institutes cannot be explained by the reported uncertainty from each institute in many cases. This means that the uncertainties reported from each institute are underestimated or that some uncontrolled parameter has an effect on the HBW measurements.
- Results of the diameter measurements on the reference indentation showed large differences between the institutes. High correlation was found between the results of reference indentation measurement and those of hardness measurement of their own indentation. The dispersion of the measurements within the institutes is much smaller than the difference between institutes. 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.

These conclusions clearly pointed out the need for an improved definition of the Brinell indentation edge, or a better defined indentation measurement procedure. This led to a discussion within the CCM-WGH of the effect of the numerical aperture (NA) of optical microscopes. Germak and Origlia [9] have found that the effect of the NA can be minimized when NA > 0.2 or 0.3. It was subsequently found that the measurement differences between laboratories in the Brinell KC could be reduced by correcting for the NA.

International Brinell test method standards prescribe requirements on the various Brinell hardness test parameters, such as for the application of force, capability of the indentation measuring system, etc., by stating permissible limits on parameter values. The goal of the CCM-WGH is to specifically define the test parameter values to minimize measurement differences between NMIs, while usually not deviating from the procedure specified in the test method standards used by industry. For example, it is not the intent of the CCM-WGH to define Brinell hardness as a measure of pressure, but rather to define the parameters of the Brinell hardness test method.

From the standpoint of ball indentation, a definition of the Brinell hardness indentation edge should ideally be based on the surface area of contact between the ball indenter and the test material while the test force is applied. However, since there is no easily implemented method to determine the contact area while under the test force, the Brinell test method specifies that the indentation is to be measured after unloading. The test method standards make the assumption that the indentation retains the shape of the ball, although, due to elastic recovery in metals, this clearly is not true. Even after unloading, there is not a simple or quick method available to measure the surface area of contact, so the test methods specify that the contact area be estimated from a measurement of the diameter of the circular projected area of the indentation. Although not explicitly required by the test methods, the diameter is usually measured with an instrument or system incorporating an optical microscope.

At this time, the CCM-WGH is debating an appropriate definition for the Brinell hardness indentation edge. Two concepts have been discussed:

(1) A practical definition based on defining requirements for the indentation measurement instruments and the measurement process [10].

(2) A physical definition based on the indenter/material contact boundary.

3.1. Practical Definition

A practical definition of the edge of a Brinell indentation would be based on an observer's perception of the indentation edge as the dark/light boundary when viewed with an optical microscope with defined parameters. It would not be based on an actual physical attribute of the indentation resulting from the indentation process except for how the shape of the indentation at the boundary zone reflects light back towards the microscope. It would be the measurement instrument and measurement process rather than the indentation edge that would be defined.

At a minimum, a practical definition would require defining parameters for all aspects of the optical microscope measurement system for which typical variations would significantly contribute to the measurement accuracy. An advantage of defining the edge of a Brinell indentation in this way is that the definition would mirror how industry estimates the indentation dimensions.

There are many parameters and influences associated with using an optical microscope to measure the diameter of a Brinell indentation, all contributing to variations in the measurement results. Studies [3],[4],[11] have shown that these influences include light intensity, incident light direction, the numerical aperture of the lens, surface roughness and the operator's subjective interpretation of the indentation edge. If each of the influence quantities can be optimized and clearly defined, then a definition of the Brinell indentation could possibly be based on the characteristics of the measurement microscope, as well as the measurement procedure. For example, the CCM-WGH is currently proposing that an optical microscope having an NA > 0.4 should be used when measuring Brinell indentation diameters.

There are several drawbacks to this type of definition. For example, there are very many designs of optical microscopes and illumination systems that would make it difficult to adequately define the requirements of all of these measurement systems. An operator's subjective decision-making process of visually choosing the indentation edge would be difficult if not impossible to define. Also, determining measurement uncertainty with respect to such a practical definition would be extremely challenging. These problems give doubt as to whether such a practical definition would provide the possibility of an unambiguous measurement. Additionally, such a definition of specifying the parameters of an optical microscope would preclude the use of any other type of measurement technique to determine the indentation surface area.

3.2. Physical Definition

A physical definition of the Brinell hardness indentation edge requires that a physical feature of the indentation can be observed and is measureable. For example, this could be the indenter/material contact boundary while under load. A second requirement is that the physical feature must be related to the indentation process, which in this case can only be the indenter/material contact boundary. Lastly, the location of the physical feature must not significantly differ from the indentation edge as historically measured using an optical microscope.

As previously discussed, it is currently impractical to measure the contact boundary while under load. In addition, the Brinell test method specifies that the indentation is to be measured after unloading. To be able to define the edge of the Brinell indentation with a physical definition, a physical feature must be present after unloading that can be observed and measured, and that is related to the indenter/material contact boundary.

Researchers at the National Metrology Institute of Japan (NMIJ, Japan), the National Physical Laboratory (NPL, UK), the Istituto Nazionale di Ricerca Metrologica (INRIM, Italy) and National Institute of Standards and Technology (NIST, USA) have investigated the Brinell indentation and have observed that the cross-sectional surface profile of a ball indentation exhibits a maximum change in gradient or slope at the edge region of a ball indentation (see Figure 1). The questions to be answered are (1) whether the maximum change in slope is related to the indenter/material contact boundary that occurred while under load and (2) whether this is the same location that is commonly judged to be the indentation edge as observed with an optical microscope? If it is determined that these questions are true, then a physical definition of a Brinell indentation is possible.

4. MODELLING BRINELL INDENTATION

It is reasonable to assume that the indenter/material contact boundary on the test material occurring while under load will physically move after unloading due to the elastic recovery in the test material. Unfortunately, the contact boundary cannot be observed with an optical microscope following the removal of the indenter.

A study was conducted at NIST to determine whether the location of the indenter/material contact boundary could be identified on the indentation surface after removing the applied test force. Ma [12] used finite element modeling (FEM) to identify the node location of the indenter/material contact boundary while under load, and then tracked the movement of

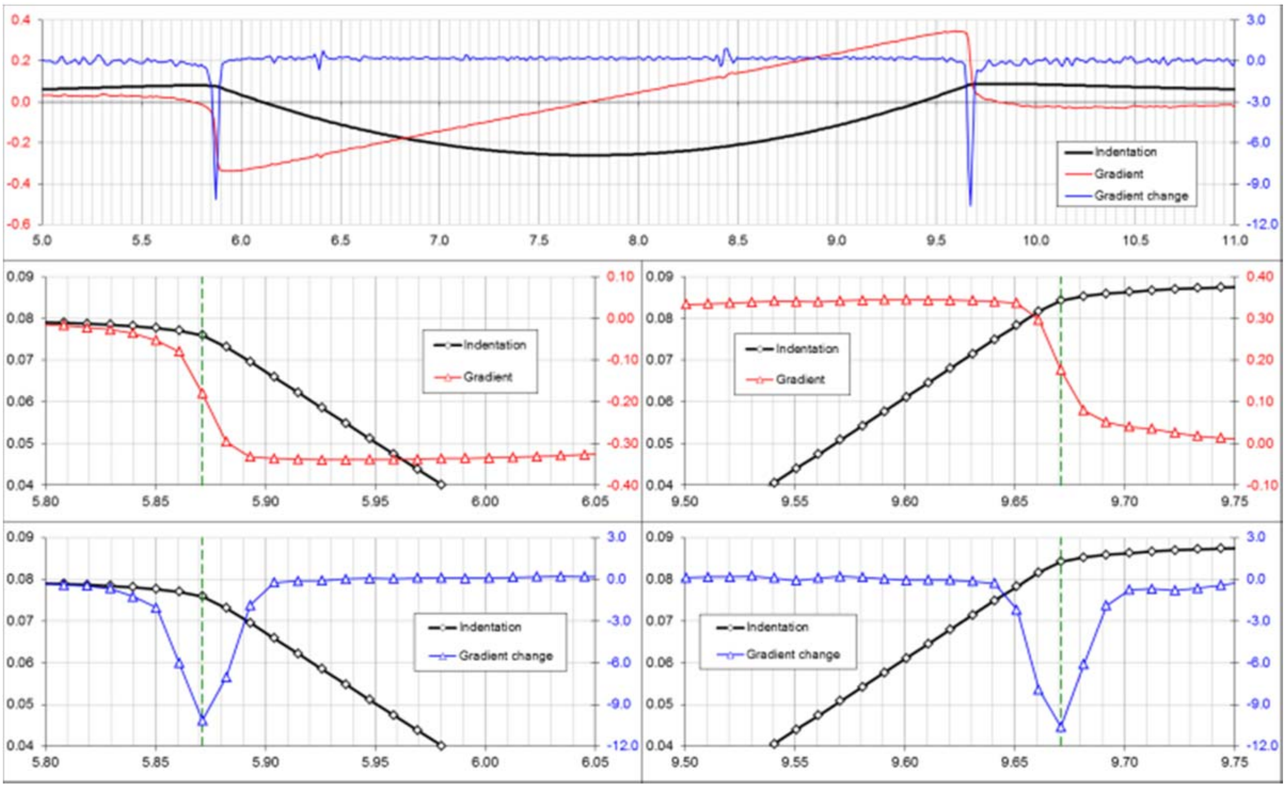

Figure 1. Cross-sectional profile of a Brinell HBW 10/3000 indentation measured at NPL using a stylus profilometer. The x-axis (mm) is the relative distance across the indentation profile. The indentation depth (black) is in mm; the corresponding gradient (red) is in mm/mm; and the gradient change (blue) is in mm/mm per mm.

the FEM node during the unloading process. The magnitude of the movement of the contact boundary has been reported by Ma [13] to vary depending on a material's strain hardening, and ratio of modulus and yield stress.

The results of the analysis showed that the location of the indenter/material contact boundary does in fact coincide with the maximum change in surface gradient or slope at the edge region of a ball indentation. Ma also found that by plotting the change of the slope, the minimum peak of the curve is the point on the indentation surface at which the boundary of the contact between the indenter ball and test material occurred while the force was applied. An example of a minimum peak from measurements conducted at NPL can be seen in the bottom two plots of Figure 1 showing the gradient change at the left and right edges of a Brinell indentation.

Additional FEM work by Ma [13] demonstrated that the correlation between the minimum peak of the slope change and the indenter/material contact boundary is consistent and independent of material parameters including the type of material, hardness level, and indentation edge pile-up or sink-in conditions.

5. MEASURING THE INDENTATION PROFILE

In order for the edge of a Brinell indentation to be defined as described above, the edge point must be measureable with sufficient resolution to be meaningful. Surface profile measurements were conducted at NIST to determine the practicality of determining the indentation diameter of Brinell indentations from a cross-sectional profile measurement. It is not as straight-forward as it would seem. There are multiple issues that must be considered.

Two approaches for measuring the indentation cross-sectional profile were investigated. The first technique was to measure across the diameter of the projected indentation area with a series of confocal microscope measurements oriented normal to the projected area of the indentation, then stitching together the images using software to obtain the full cross-sectional profile. Two significant problems were encountered when using this technique. The first was that the confocal microscopes that were available had difficulty in imaging larger surface angles at the indentation edge for deep indentations. Unfortunately, that is the area of most interest.

The second issue was in measuring larger indentations in which multiple images were needed to obtain the needed length resolution. The stitching software introduced dimensional errors due to the stitching process which multiplied with each additional image. These two issues alone prevented using these instruments to measure the indentation diameter. Perhaps the confocal microscope technique can be viable with the use of an improved lens system that can resolve larger surface angles, and with the use of a traversing stage having an accurate displacement sensor to eliminate the need for stitching multiple images.

The second technique used a contact stylus profilometer to measure the surface profile by making a linear trace across the indentation surface through the center point of the indentation. It is important that the measurement system has sufficient 2D resolution to adequately define the indentation edge. This is a similar technique as was used by NPL to produce the measurement example given in Figure 1. This technique proved to be successful; however, there are also issues that must be considered.

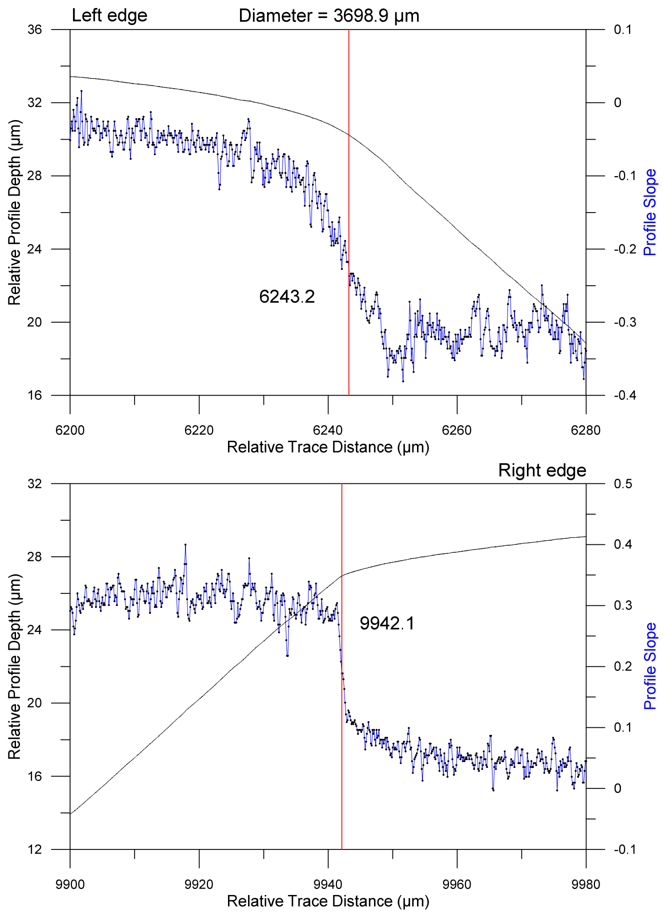

Figure 2. NIST surface profile measurements of the left and right edges of a ~270 HBW 10/3000 indentation, as well as plots of the profile slope.

As compared to an FEM model of an indentation, the surface of a real indentation is not perfectly smooth exhibiting roughness and imperfections due to material grain structure, inhomogeneity, etc. The effect of the surface roughness can be seen in Figure 2, which shows NIST surface profile measurements of the left and right edges of a ~270 HBW 10/3000 Brinell indentation, as well as plots of the profile slope. It is interesting to note that the left and right edges are dissimilar in form. These surface irregularities are amplified when analyzing the slope of the indentation surface, and are amplified further when analyzing the change in slope producing significant variations or “noise” in the data. The effect of the surface roughness on the profile slope data is evident in Figure 2, and tends to mask the maximum change in slope in the slope plots. In plotting the change-in-slope data, the magnitude of the noise produced by the surface roughness becomes too great to be usable. Applying filters to the surface profile data can significantly reduce the noise levels in the data as shown by Ma [13].

It is imperative that the measuring stylus traverse across the actual center of the indentation so that the true diameter is measured rather than an adjacent but shorter chord line. Perfect alignment to the center is difficult and must be verified. This was accomplished for the NIST measurements by making multiple parallel traces at known increments through the central region of the indentation and determining the resulting diameters. Figure 3 illustrates the results of this technique showing that the true diameter is within the nine parallel traces spaced at 25 µm increments separation. The preliminary data

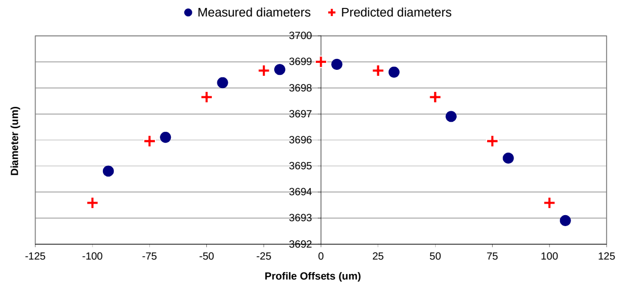

Figure 3. Diameter measurements (solid circle) from nine parallel traces at 25 µm increments through the central region of the Brinell indentation. Also shown are predicted diameter values (cross) based on a circular indentation.

shown in Figures 2 and 3 are given only to illustrate the technique that is being investigated. A full uncertainty analysis is yet to be completed; however, the uncertainty based solely on the instrument measurements is estimated as being much smaller than ±1 µm (k = 2). The major contribution to the measurement uncertainty is due to determining the location of the maximum change in gradient.

6. COMPARISON WITH OPTICAL MICROSCOPES

A final factor in deciding if it is appropriate for the Brinell indentation edge to be defined by a physical definition is to determine how well measurements of the indentation diameter measured as discussed above compare with measurements using an optical microscope. NIST collaborated with a commercial laboratory that produces Brinell reference blocks asking them to measure two indentations for which the diameters had previously been determined based on the surface profiles. The commercial company measured the Brinell indentation diameters with an optical microscope that uses a camera/image-analysis system to determine the projected area of the indentation. Table 1 summarizes the results.

Although additional work is needed, preliminary comparisons indicate reasonable agreement between indentation diameters measured from the indentation profile and using optical microscopes. Although a thorough uncertainty analysis has not yet been completed, the uncertainty (k = 2) of the indentation diameters measured from the indentation profile is estimated to be no greater than ±2 µm, and no greater than ±4 µm for the optical microscope measurements. It should be noted that for the higher hardness measurements (~500 HBW 10/3000), the difference between the profilometer and optical microscope measurements is not covered by the expanded uncertainties of the instruments. However, the uncertainty analyses are not based on the same criteria. In the case of the indentation diameter measured from the indentation profile, the uncertainty is with respect to resolving and measuring the maximum rate of change of gradient of the curved indentation surface profile. In the case of the optical microscope measurements, the uncertainty is based

Table 1. Comparison of Brinell indentation diameter values measured at NIST based on the indentation surface profile and values based on optical measurements by a commercial calibration laboratory.

Approximate HBW 10/3000	Surface Profile Measurement	Optical Microscope Measurement	Measurement Difference
270	3699 µm	3701 µm	2 µm (0.3 HBW)
500	2740 µm	2733 µm	7 µm (2.6 HBW)

on measuring a flat glass reference standard, which may not be representative of measuring an actual indentation.

Hou et al. [14] detail complementary work investigating the measurement of low-force Rockwell indentations by three different techniques, including both contact and non-contact methods, together with associated FE modelling. This work concludes that the 2D optical measurements overestimated the contact area, particularly when pile-up was present, but that the two 3D measurement methods were in good agreement.

7. CONCLUSIONS AND PROPOSAL

In cases where there is no distinct physical measurand that can be observed or directly measured for a test parameter, it may be reasonable to define the parameter in terms of a well-defined measurement system or measurement process as a practical definition. This would be the case for the smooth curving edge of a Brinell indentation if there was no identifiable physical boundary that could be measured. However, we have shown that a location on the surface of a Brinell indentation, related to the indenter/material contact boundary under load, can be identified and measured. This is a compelling argument for defining the Brinell indentation edge by this physical definition.

Therefore we propose the following definition for the Brinell hardness indentation:

"*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.*"

The content of this paper and definition of the indentation lead to the following physical definition for the edge of a Brinell hardness indentation:

"*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.*"

Although we recommend defining the Brinell indentation edge as a physical definition, measuring the edge based on this definition is not a practical method for making routine Brinell hardness measurements. Currently, measuring and analyzing the indentation surface profile is a difficult and time consuming exercise. A promising application of the physical definition is for the calibration of reference standards of Brinell indentations with certified diameter measurements for verifying optical microscope measuring systems.

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