Practical points of Brinell indentation diameter measurement using optical microscope

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Abstract. The indentation diameter measurement is the important issue for Brinell hardness test. The large dependence of optical system is found in the first world-wide international comparison for Brinell hardness, conducted in 2005. After the comparison, some studies was carried out especially for this issue. Finally, the definition regarding the Brinell indentation edge was studied. However, the practical guide for good measurement condition of Brinell indentation diameter by using measurement microscope is not detailed explained. In this paper, we present the cause of the numerical aperture dependence of Brinell indentation diameter and also present the practical guideline of the selection of objective lens used to the observation.

1. Introduction

Brinell hardness is oldest and one of popular hardness test method and is used to obtain averaged hardness value of the material because of the large size of indentation. CCM Working group on hardness conducted the international comparison on Brinell hardness block calibration in from 2003 to 2005 for harmonize the international hardness scale. In this comparison, non-negligible deviation was found in measured indentation diameter due to difference of optical measurement system. After the artifact circulation, some investigations were carried out and reported[1,2]. It was concluded that the optical system, especially low numerical aperture (N.A.) of the objective lens of microscope, was main cause of the deviation. Typical Brinell indentation has mm size indentation in diameter, and it may be use the very low magnification and low numerical aperture objective lens to obtain whole image of Brinell indentation, if the digital image analysis applied with circular fitting. In the process of the reporting, we discussed the definitions of the Brinell indentation and reported [3]. The practical definition is determined as N.A. > 0.4, that is mainly from N.A. dependence of Brinell indentation diameter.

The report of pilot study on international comparison had been circulated in the final form [4]. In this report, we would like to introduce our measurement results and discussed the effect of optical measurement of Brinell indentation diameter.

2. Experimental results

2.1 Numerical aperture dependence of Brinell hardness

The Brinell indentation of 250 HBW, 350 HBW and 450 HBW with scales 10/3000, 5/750, 2.5/187.5 and 1/30 was measured by using 6 objective lenses (N.A. = 0.7, 0.55, 0.4, 0.3, 0.14 and 0.055). Illumination condition is epi-illumination. Figure 1 shows the obtained results. Hardness is indicated the
difference from the results of N.A=0.4 as a reference. The results show the same trend, the calculated hardness acutely decreasing with decreasing numerical aperture of objective lens less than 0.3. That shows the same trend in reported by Dr. A. Germak et al.[2].

Figure 1. Numerical Aperture (N.A.) dependence of Brinell hardness. Differences from the result obtained by N.A.=0.42.

2.2 Surface profile of the indentation edge.

The surface profile near the Brinell indentation edge was observed using confocal microscope with N.A. = 0.95. The typical 3D image for 250 HBW 5/750 is shown in figure 2 and cross-sectional profile near the indentation edges for 250, 350 and 450 HBW 5/750 are shown in figure 3. The differential of the cross-sectional profile (gradient) is calculated and indicated in figure4. The moving-average of 5 points were applied due to the noise of differential calculation. Only for 250 HBW results was shown in the figure. The gradient, was indicated by “Sin A”, which is calculated by the incline angle, A from original surface and comparable to the numerical aperture as in the following discussion.

Figure 2. Three-dimensional profiles of 250 HBW 5/750 Brinell indentation near edge.

Figure 3. Cross-sectional profile near the Brinell indentation edge.
Figure 4. Calculated gradient for 250 HBW 5/750. The gradient is indicated by N.A. (Sin A).

In the cross-sectional profile, the pile-up due to the material flow of the indentation is clearly observed in figure 2 and 3. The edge point was determined by manually as the highest gradient change point. The cross-sectional profiles change depending on hardness. Most significant pile-up is observed at 250 HBW 5/750 indentation. The top of pile up is observed about 70 \( \mu m \) from edge. The gradient is increasing with decreasing the distance from edge.

In the figure 4., the edge, distance zero point, is the same point which is used in figure 3. The zero-point looks not accurately determined as mentioned above, however, it is correctly determined. This is because the effect of moving average, which is applied for remove large noise of differential calculation. The gradient looks almost constant inside the edge. The Sin \( A \) is about 0.32 for inside of the indentation and that is decreasing about 0.1 at around the edge and gradually decreasing. After crossing x-axis at about 70 \( \mu m \) (top of pile-up) in distance from edge and continue decreasing up to 180 \( \mu m \).

3. Discussion

3.1 Estimation of incline angle at Brinell indentation edge

The incline angle, \( A \) at the Brinell indentation edge can be estimated by indentation diameter, \( d \) and diameter of Ball indenter, \( D \) as,

\[
d/D = \sin A = \text{N.A.}
\]

Where, the N.A. is the parameter that can be directly comparable to the numerical aperture of the objective lens. The actual edge angle will be much smaller than the estimated value, because of shallowing of indentation due to the elastic recovery after unloading. The estimated incline angle and corresponding numerical aperture are shown in table 1 and 2, respectively.

3.2 The relation between numerical aperture of microscope objective and surface profile

The following discussion, we assume illumination system as an epi-illumination, in other words, the illumination and reflection observation system has the same axis and the same numerical aperture. The light intensity of the image observed by microscope is depending on gradient of observing surface. The parameter Sin \( A \), surface N.A., is the comparable parameter directly to the numerical aperture of objective lens. The image getting dark with increasing surface N.A. The no light returned back to the objective lens, when the surface N.A. increasing much larger than objective N.A.
Figure 5 indicates the typical example observed by N.A. 0.055 objective lens. Bright ring is observed very near the apparent indentation edge. This bright ring is the reflection from top of pile-up. After the bright ring, the dark ring is observed depending on the gradient increase after the top of pile-up.

![Dark point due to pile-up](image)

**Figure 5 typical example of low numerical aperture observation of Brinell edge. N.A. 0.055 objective lens was used.**

To detect the Brinell indentation edge, the gradient changing point shall be detected correctly. In the case of Figure 4, the point is the decreasing point that is surface N.A. changing from about 0.3 to 0.1. To detect this point, the microscope N.A. shall be much larger than 0.3. The objective N.A. = 0.1 is used, for instance, the difference is about 5 \( \mu \text{m} \sim 10 \mu \text{m} \) for one-side of the indentation edge, is about 10 \( \mu \text{m} \sim 20 \mu \text{m} \) for both side. That is the cause of large difference found in the international comparison.

The corresponding N.A. calculated from previous section, is 0.38 for 250 HBW 5/750 that is used above discussion. the N.A. experimentally observed is about 0.32. The estimated N.A. from equation is slightly larger than that of observed. However, the estimated indicated in table 2 is the one of good guideline to the selection of objective lens to measure the Brinell indentation diameter.

### 4. Summary

The one of selection guide for numerical aperture of objective lens, which is used for Brinell indentation diameter measurement, was presented in this paper. The relationship between microscope N.A. and surface profile also presented in the case of epi-illumination system. Another suitable combination is acceptable, such as low-numerical aperture objective and high N.A. illumination with ring light. Practically, presented condition indicate that A) both of inside of the indentation and pile-up shall be observable, and B) edge of indentation can be detectable with appropriate contrast image. That condition B is unsatisfied if the high hardness and low force-diameter index is used.

The experimental results and discussions are presented in this paper. Some of the results is already presented in closed meeting on the CCM Working group on hardness meeting. Diameter of Brinell indentation is one of difficult measurement item. We hope these results help the harmonization of Brinell hardness value.

### References

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