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A method to determine the spherical indentation contact boundary diameter in elastic–plastic materials

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ABSTRACT

Significant measurement differences in Brinell spherical hardness test results have been continually observed worldwide largely due to the edge of the indentation not being a distinct boundary. The boundary is instead a curved surface from either material piling up (pile-up) or sinking in (sink-in), making it difficult to clearly resolve the edge of the indentation and thus to determine the indentation diameter from the optical microscope measurement. The indenter/material contact boundary under the test force should be the basis for the Brinell spherical indentation diameter; however, the contact boundary cannot be observed using an optical microscope after the indenter is removed as is required by the test methods. It is also a critical issue to derive the contact diameter from load depth relations in the widely used instrumented indentation. In this study, finite element analysis (FEA) was used to study the contact location at the indentation boundary. Meanwhile, Brinell hardness indentations were made and measured. The characteristics of the indentation profiles from the experimental measurement showed the same trend with that from FEA models. Various parameters that would affect the indentation pile-up or sink-in conditions, including the material's strain hardening, ratio of Young's modulus to yielding stress, indentation depth and friction, were studied from the FEA model. A physical measurement method is developed to determine effectively the indentation contact position. Applying the new method, the deviation of the measured indentation diameter from the actual contact diameter was estimated for each indentation.

1. Introduction

The Brinell hardness test has continued to be used extensively in industry for quality control and acceptance testing of metallic materials and products since it was proposed in 1900 by a Swedish researcher J.A. Brinell (Chandler, 1999). By varying the test force and ball size, nearly all metals can be tested using a Brinell hardness test. The general significance of the Brinell test is that the hardness measurement can be empirically related to uniaxial material properties as shown by Meyer, O'Neill, Tabor, et al. (Biwa and Storakers, 1995; Hill et al., 1989; O'Neill, 1967; Tabor, 1951). As an empirical indentation hardness test, it provides useful information about metallic materials which may correlate to tensile strength, wear resistance, ductility, or other physical characteristics of metallic materials (ASTM, 2001).

The Brinell hardness test involves indention of the test material by an accurately controlled test force applied to a tungsten-carbide ball indenter. After the removal of the indentation force and indenter, the recovered mean diameter of the indentation, d (unit of mm), is determined by measuring the diameter of the two-dimensional projected area of the round indentation using an optical microscope or an optical image analyzing system. The Brinell hardness

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number, *HBW*, is calculated by dividing the test force F (unit of N) by the curved surface area of indentation which is assumed to be spherical and of the diameter of the ball D (unit of mm) as (ASTM, 2001):

$$HBW = 0.102 \times \frac{2F}{\pi D(D - \sqrt{D^2 - d^2})} \quad (1)$$

Although the Brinell hardness test has been widely used by industry for more than 110 years, significant measurement differences have been continually observed worldwide, even in the secondary calibration laboratories that calibrate test block reference standards. These differences propagate down to the industrial level with an enlarged amount. The main cause of this problem is due to a considerable difficulty in measuring the diameter of indentation. As observed by many researchers (Lysaght, 1949; Norbury and Samuel, 1927; Small, 1960), the edge of the indentation is not a distinct boundary. Sometimes there is a mounding of the specimen material around the indentation causing the indenter/material contact area to extend above the original surface of the specimen, which we will refer to as "pile-up". At other times the edge of the area of contact is below the original surface, which we will refer to as "sink-in". In some cases, there is no sharp visible line of demarcation between the indentation and the surrounding surface; one surface merely rounds off into the other. In all cases, there is uncertainty as to the portion of the visible indentation which was actually in contact under load.

The phenomenon of pile-up or sink-in in the indentation process is known to significantly influence the determination of the contact area and indentation contact diameter. This is particularly a problem for instrumented indentation testing, which is known as depth-sensing indentation, where the indentation force and depth are continually recorded to extract the materials mechanical properties like the hardness and elastic modulus (Oliver and Pharr, 1992, 2004). It is a challenge to accurately determine the contact radius from only force-depth data due to the pile-up/sink-in effect. Doing so was found to result in errors of as much as 60% for conical indentations on aluminum (Bolshakov and Pharr, 1998). Analytical corrections for the pile-up or sink-in are often applied with varying success in determining the true contact area. It may be helpful to instead directly measure the contact area as proposed here.

Early experimental studies of surface deformation around a spherical indenter found that the amount of pile-up and sink-in was related to the strain-hardening exponent of the materials (Norbury and Samuel, 1927; O'Neill, 1967; Tabor, 1951) and these were expressed as functional relationships (Francis, 1976; Hill et al., 1989; Matthews, 1979). From finite element analysis (FEA) simulations, the pile-up/sink-in is found to be related, not only to strain hardening n (Alcala et al., 2000; Hill et al., 1989), but also to yield strain (the ratio of yield strength Y to elastic modulus E), indentation ratio (indentation depth h over indenter radius R) (Ai and Dai, 2008; Hill et al., 1989; Kim et al., 2006) and contact friction (Cheng and Cheng, 1998; Habbab et al., 2006; Karthik et al., 2012). The effect of these parameters on the evolution of pile-up/sink-in has been studied with a wide range of materials (Maneiro and Rodriguez, 2005; Song and Komvopoulos, 2013; Taljat and Pharr, 2004; Taljat et al., 1998). It is critical to develop a method to effectively determine the indentation contact radius.

In industry, Brinell hardness indentations are measured using optical microscopes by observing the dark-to-light transition at the indentation edge. Measuring instruments can vary from simple hand-held microscopes with a 20–40× 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 surface curvature of the pile-up or sink-in material at the indentation edge (Machado et al., 2007). 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 line to appear to occur at varying locations (Barbato and Desogus, 1986; Germak and Origlia, 2007; Machado et al., 2007; Petick, 1996).

Up to now, it has not been possible to identify a distinct physical edge of an indentation when using an optical microscope. It has been found that the indistinct nature of the edge of an indentation is probably the greatest single factor contributing to the lack of agreement in Brinell numbers obtained by different observers testing a given material (Barbato and Desogus, 1986; Petick, 1996). Therefore it is necessary to define and standardize a clear physical indentation diameter measurement position (ASTM, 2001; Germak et al., 2010).

Theoretically, the ideal Brinell hardness value should be based on the indenter/material contact area while under the applied force. However, there are practical industrial limitations that must be considered. In-situ measurement of the indentation diameter under load is difficult and not practical for most Brinell testing. Therefore, the indentation diameter is measured after removing the indenter and indentation force. This measurement is only an approximation of the diameter of the indenter/material contact area while under the indentation force since the contact boundary occurring while under loading cannot be optically identified after unloading. The measured diameter after the indentation force is removed may be quite different because of the elastic recovery of the indentation. The challenge is to define an effective procedure to measure the real diameter of the projected indentation contact area after removing the load. The objective of this research is to determine the most appropriate definition of the diameter of a Brinell indentation that also allows its unambiguous measurement in the unloaded condition.

We investigated the Brinell indentation contact diameter from confocal microscope measurement, stylus profilometer and FEA modeling in our former research (Ma et al., 2007, 2012). In this study, FEA models were developed to study the location of contact boundaries at the edges of Brinell hardness indention cross-sectional profiles. From the FEA models, the location of the contact boundary under load is determined and is then tracked after removing the load. The indention profile shapes from FEA models were confirmed by examining actual Brinell indentations. The contact position was investigated from