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A dual conical indentation technique based on FEA solutions for property evaluation

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ABSTRACT

The sharp indenters such as Berkovich and conical indenters have a geometrical self-similarity so that we can obtain only one parameter from an indentation loading curve, which makes different materials have the same load–displacement relation. Most studies to evaluate elastic–plastic properties by using the geometrical self-similar indenter have therefore tried to use dual/plural indentation techniques, on the basis of the concept of representative strain/stress varying with the indenter angle. However, any suggested representative concept is not universally operative for real materials. In this work, we suggest a method of material property evaluation without using the concept of representative strain. We begin the work by studying the characteristics of load–depth curves of conical indenters via finite element (FE) method. From FE analyses of dual-conical indentation, we investigate the relationships between indentation parameters and load–depth curves. The projected contact diameter is expressed as a function of the indenter angle, tip-radius, and material properties, which allows us to simply predict the elastic modulus. Two mapping functions for two indenter angles (45° and 70.3°) are presented to find the two unknowns (yield strain and strain-hardening exponent) via dual indentation technique. The method provides elastic modulus, yield strength and strain-hardening exponent with an average error of less than 5%. The method is valid for any elastically deforming indenters. We also discuss the sensitivity of measured properties to the load–displacement curve variation, and the difference between conical and Berkovich indenters.

1. Introduction

The instrumented indentation test is a method to extract material properties from indentation load–depth curves with micro specimens or parts of mechanical structures in use (Chen et al., 2006, 2010; Cook and Pharr, 1990; Giannakopoulos and Larsson, 1997; Giannakopoulos and Suresh, 1999; Huber and Tsakmakis, 1999a,b; Kermouche et al., 2008; Lan and Venkatesh, 2007; Lee et al., 2005; Liao et al., 2009; Ogasawara et al., 2006a,b, 2009; Oliver and Pharr, 1992; Suresh and Giannakopoulos, 1998; Xia et al., 2007). The contact area and load–displacement curves to measure the hardness and elastic modulus are fundamental and important data for indentation test. However, it is quite difficult to measure or predict the contact diameter due to imperfection or tip-blunting of indenter. Based on Hertz contact mechanics, many studies on evaluating the actual contact area and geometric deviation of indenter from its nominal geometry have been performed (Borodich et al., 2003; Borodich and Keer, 2004).

There should be a one-to-one match between the load–depth curve obtained from an indentation test and its material properties. However, some materials having different material properties may show the same load–depth curve due to the geometrical self-similarity of sharp indenters (Capehart and Cheng, 2003; Chen et al., 2007; Cheng and Cheng, 1998; Lee et al., 2008; Tho et al., 2004). Chen

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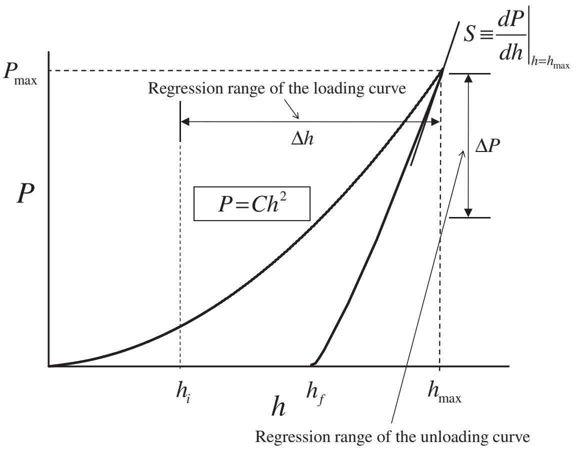

Fig. 1. Schematic illustration of a P–h curve of elastic–plastic material under instrumented sharp indentation (Lee et al., 2008).

et al. (2007) and Lee et al. (2008) demonstrated that countless materials can have the same Kick's law coefficient C despite their different material properties. Dual (plural) sharp indenters with dissimilar angles can be therefore used to solve this problem. In previous studies (Bucaille et al., 2003; Cao and Lu, 2004; Chollacoop et al., 2003; Ogasawara et al., 2005, 2006a; Shim et al., 2008), unique solutions were attempted by using the concept of representative strain ε_R which varies with the half-included angle of indenter.

The loading curves from sharp indenters generally follow the Kick's law relation.

$$P = Ch^2 \tag{1}$$

Here P is the indentation load, h is the measured depth from reference surface and C is the coefficient of the Kick's law. P_{max} is the maximum load at the maximum indentation depth h_{max}, and the initial unloading slope S is defined as dP/dh at $h = h_{max}$ as depicted in Fig. 1. Kick's law is valid for the ideal sharp indenter, but the tip-radius effect breaks the Kick's law and the corresponding self-similarity. For eliminating the effect of tip-radius, Lee et al. (2008) suggested the corrected Kick's law as following equation.

$$P = C(h + h_g)^2, \quad h_g = R\left(\frac{1}{\sin\alpha} - 1\right) \tag{2}$$

Here h_g is the gap between the indenters with zero and finite tip-radius (Fig. 2). Eq. (2) is not valid when the effect of the tip-radius is dominant in shallow indentation. However, as the indentation depth increases the effect of the tip-radius decreases so Eq. (2) became valid. In Fig. 2, h_t means the expected indentation depth ($h_t = h + h_g$) for an ideally sharp indenter.

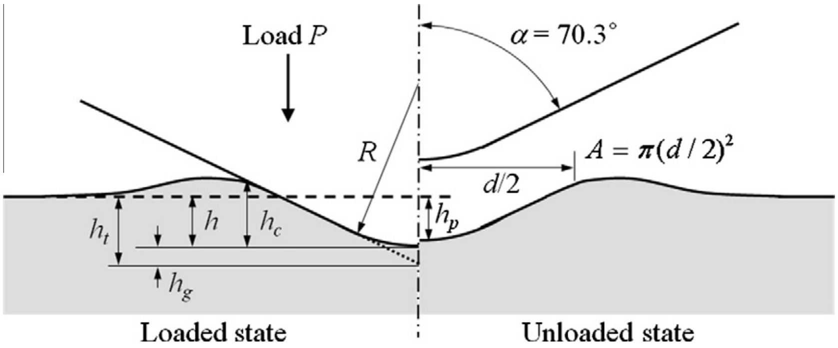

Fig. 2. Schematic of sharp indentation profiles with finite tip-radius.

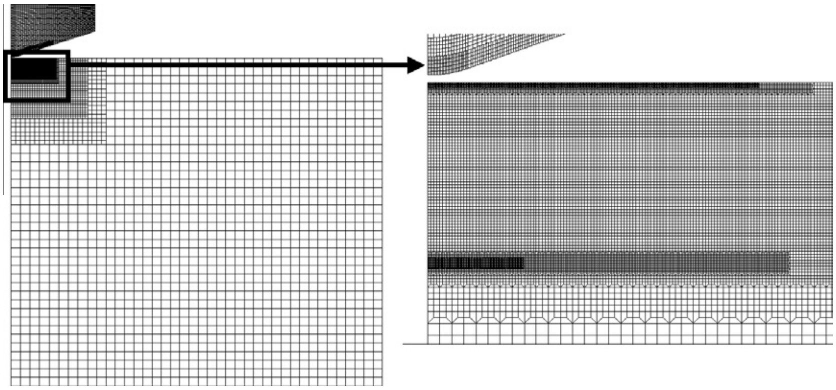

Fig. 3. Overall mesh design using axisymmetric conical indenter.