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Comparison between Berkovich, Vickers and conical indentation tests: A three-dimensional numerical simulation study

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ABSTRACT

Three-dimensional numerical simulations of Berkovich, Vickers and conical indenter hardness tests were carried out to investigate the influence of indenter geometry on indentation test results of bulk and composite film/substrate materials. The strain distributions obtained from the three indenters tested were studied, in order to clarify the differences in the load–indentation depth curves and hardness values of both types of materials. For bulk materials, the differentiation between the results obtained with the three indenters is material sensitive. The indenter geometry shape factor, β, for evaluating Young's modulus for each indenter, was also estimated. Depending on the indenter geometry, distinct mechanical behaviours are observed for composite materials, which are related to the size of the indentation region in the film. The indentation depth at which the substrate starts to deform plastically is sensitive to indenter geometry.

1. Introduction

Depth-sensing indentation tests are used to determine the hardness and the Young's modulus of bulk materials and thin films. Usually, Berkovich and Vickers indenters are used. Thus, the importance of understanding the relationship between the results of both indenters is obvious. In addition, the conical geometry is commonly used in bi-dimensional numerical simulation studies as equivalent to the Berkovich and Vickers indenters. Therefore, it is important to compare the results obtained using the three indenters.

To our knowledge, studies concerning the comparison of Berkovich, Vickers and conical indentation results are unusual. Only, a few experimental and numerical investigations (Rother et al., 1998; Min et al., 2004), concerning the equivalence of the results obtained from specific bulk materials, have been performed. Min et al. (2004) studied the influence of the geometrical shape of Berkovich, Vickers, Knoop and conical indenters on load–indentation depth curves and the strain field under the indentation for a copper specimen. However, the comparison of the indentation behaviour of bulk and composite materials with different indenter geometries still needs further investigation.

In the current study, three-dimensional numerical simulations of the indentation tests, in bulk and composite materials, were performed using the Berkovich, Vickers and conical indenters. Regarding bulk materials, a systematic study is presented which has a ratio between the residual indentation depth after unloading (h_f) and the indentation at the maximum load (h_{max}) in the range $0.20 < h_f/h_{max} < 0.98$. The geometrical correction factor needed to determine the Young's modulus, was also studied for the three indenters, for both bulk and composite materials. With regard to thin films, the study mainly focuses on the beginning of plastic deformation in the substrate, which defines the critical penetration depth above which the composite hardness results depend on the substrate's mechanical properties. The indentation test results, obtained using the three indenter geometries, are examined by comparing the load–indentation depth curves, the hardness values and the strain distributions in the indentation region.

2. Theoretical aspects

As mentioned above, depth-sensing indentation measurements are used to determine the hardness and the Young's modulus. The hardness, H_{IT}, is evaluated by (e.g., Oliver and Pharr, 1992)

$$H_{IT} = \frac{P}{A}, \qquad (1)$$

where P is the maximum applied load and A is the contact area of the indentation, at the maximum load. The reduced Young's modulus, E_r, is determined from (e.g., Sneddon, 1965; Oliver and Pharr, 1992)

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$$E_r = \frac{\sqrt{\pi}}{2\beta}\frac{1}{\sqrt{A}}\frac{1}{C}, \tag{2}$$

where β is the geometrical correction factor for the indenter geometry and C is the compliance. The specimen's Young's modulus, E_s, is obtained using the definition:

$$\frac{1}{E_r} = \frac{1-\nu_s^2}{E_s} + \frac{1-\nu_i^2}{E_i}, \tag{3}$$

where E and ν are the Young's modulus and the Poisson's ratio, respectively, of the specimen (s) and of the indenter (i). In this study, the indenter was considered rigid, and so $(1-\nu_i^2)/E_i = 0$.

The accuracy of the hardness and Young's modulus results, obtained with Eqs. (1)–(3), depends on the evaluation of contact area and compliance. In this study, the contact area, A, was evaluated using the contour of the indentation (see next section). Using this approach, contact area results are independent of the formation of pile-up and sink-in. The compliance C was evaluated by fitting the unloading part of the curve load–indentation depth, $(P-h)$, using the power law (Antunes et al., 2006)

$$P = P_0 + T(h-h_0)^m, \tag{4}$$

where T and m are constants obtained by fit and h_0 is the indentation depth which corresponds to a load value P_0, during unloading. In the fits, 70% of the unloading curve was used (Antunes et al., 2006).

Furthermore, another approach can be used for evaluating hardness and Young's modulus, allowing the Young's modulus to be obtained when the hardness is known, and *vice-versa*. This approach proposed by Joslin and Oliver (1990), uses the following equation, obtained by combining Eqs. (1) and (2)

$$\frac{P}{S^2} = \frac{\pi}{4\beta^2}\frac{H_{IT}}{E_r^2}. \tag{5}$$

The ratio between the maximum applied load (P) and the square of the stiffness ($S = 1/C$), P/S^2, is an experimentally measurable parameter that is independent of the contact area and so of the penetration depth (Joslin and Oliver, 1990). Moreover, if the hardness and the Young's modulus are known, the determination of the correction factor β is another useful application of Eq. (5).

3. Numerical simulation and materials

The numerical simulations of the hardness tests were performed using the HAFILM in-house code, which was developed to simulate processes involving large plastic deformations and rotations. This code considers the hardness tests a quasi-statistic process and makes use of a fully implicit algorithm of Newton-Raphson type (Menezes and Teodosiu, 2000). Hardness tests simulations can be performed using any type of indenter and take into account the friction between the indenter and the deformable body. A detailed description of the HAFILM simulation code has previously been given (Antunes et al., 2007).

Numerical simulations of the hardness tests were performed using Berkovich, Vickers and conical indenters. These three geometries are modelled with parametric Bézier surfaces, which allow a fine description of the indenter tip, namely an imperfection such as the one which occurs in the real geometry (Antunes et al., 2002). For ideal Berkovich, Vickers and conical indenter geometries with half-angles of 65.27°, 68° and 70.3°, respectively, the ratios between the projected area and the square of the indentation depth are equal to 24.5, for all cases. In this study, the three indenters, shown in Fig. 1, were modelled with tip imperfections, which consist in a plane normal to the indenters' axis. The Berkovich, Vickers and conical indenter tips have triangular, rectangular and circular shapes, respectively, and an area of approximately 0.0032 μm^2.

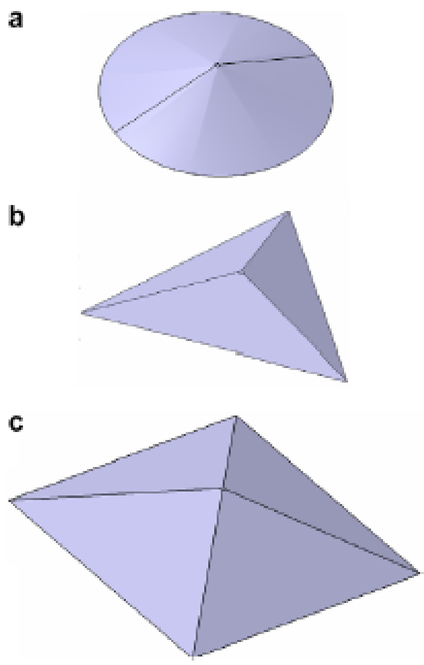

Fig. 1. Indenters geometry: (a) conical; (b) Berkovich; (c) Vickers.

This value corresponds to the imperfection usually observed in experimental Berkovich indenters (Antunes et al., 2007). Due to the imperfection at the tip, the area function of the indenters differs from the ideal. Table 1 presents the area functions of the indenters used in the numerical simulations. As can easily be seen, the three area function equations in this table represent equivalent evolutions of the area *versus* the indentation depth, in spite of their dissimilarity.

The test sample used in numerical simulations of bulk materials has both radius and thickness of 40 μm. It discretization was performed using three-linear eight-node isoparametric hexahedrons. The same sample was used in the simulation of the composite film/substrate materials. In those cases, a coating with a thickness equal to 0.5 μm (nine layers of elements in the film) was added. Due to geometrical and material symmetries in the $X = 0$ and $Z = 0$ planes, only a quarter of the sample was used in the numerical simulation of the Vickers and conical hardness tests. For the Berkovich simulation, only a symmetry condition in the $X = 0$ plane can be adopted. Thus, a half of the sample was used. In this context, the finite element meshes used in the numerical simulations with the Vickers and conical indenters were composed of 5832 elements for the bulk materials and 9072 for the thin films. In the case of the Berkovich simulations the number of elements was 11664 for the bulk materials and 18344 for the thin films. In all meshes the size of the finite elements in the indentation region was about 0.055 μm. The mesh refinement was chosen in order to provide accurate values of indentation contact area (Antunes et al., 2006).

Table 1
Area functions of the Vickers, Berkovich and conical indenters. The ideal indentation depth for the area A is: $h = \sqrt{A/24.5}$.

Indenter	Area function, A (μm^2)
Berkovich	$24.675h^2 + 0.562h + 0.003216$
Vickers	$24.561(h+0.008)^2 + 0.206(h+0.008)$
Conical	$24.5(h+0.011427)^2$