Materials and Design 49 (2013) 406–413

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

A method to take account of the geometrical imperfections of quasi-spherical indenters

P. Brammer [a,b,*], X. Hernot [a], G. Mauvoisin [a], O. Bartier [a], S.-S. Sablin [b]

[a] LGCGM, 20 Avenue des Buttes de Coësmes, 35708 Rennes Cedex, France
[b] Technocentre Renault, Engineering Cost Control Department, 1 Avenue du Golf, 78288 Guyancourt Cedex, France

ARTICLE INFO

Article history:
Received 21 November 2012
Accepted 11 January 2013
Available online 14 February 2013

Keywords:
Instrumented indentation
Geometrical imperfection
Reverse analysis
Stress–strain curve

ABSTRACT

Perfect indenter geometry is quite difficult to manufacture, especially in the nano and macro scales. Indentation curves obtained with imperfect indenter geometry can show strong differences with those obtained with assumed perfect indenter geometry, thereby leading to erroneous data exploitation results.

This numerical study brings out the effect of imperfect spherical indenter geometry on indentation load–penetration depth curves, and on the mechanical properties identified by a reverse analysis model based on ideal spherical geometry. It is shown that a method to take account of geometrical imperfections is essential. Two correction methods based on geometrical and physical considerations are assessed, as well as the relevance of the use of the penetration data or the contact data. A method based on the equality of mean contact pressures and indenter volumes under the contact surface is found to be most relevant, as confirmed by the quality results obtained after application of a reverse analysis model.

The proposed method is of particular interest in the case of the use of an imperfect indenter whose profile is accurately known.

1. Introduction

The instrumented indentation test allows for an evaluation of mechanical properties of materials at macro, micro, and nanoscales. The major assets of this test are its easy application at small scales and its quasi nondestructive aspect. The indentation data, or indentation curve, is obtained by continuously measuring the applied load F and penetration depth h of a stiff indenter of known geometry normally to the surface of the tested sample. Fig. 1 shows the geometric values of interest during the indentation by an indenter of arbitrary axisymmetric shape, in the case of the creation of either pile-up (Fig. 1a) or sink-in (Fig. 1b) at the surface of the sample. These values are referred to as the penetration depth h, the contact depth h_c, the surface contact radius a, and the contact radius a_c.

Early data analysis methods [1–3] were aimed at evaluating elastic modulus and hardness without the observation of a residual imprint which is required by standard hardness tests. These methods are described by the international standards on instrumented indentation [4–7]. Methods were also proposed to evaluate flow properties of materials [8–21]. These methods, for which no standards are available, are either based on a representative stress–strain approach and require the evaluation or measurement of the contact radius a_c at discrete points [8,9], or on reverse analysis models which only require the F–h data [10–21].

Most data analysis methods are based on ideal indenter geometry. However, perfect geometry is quite difficult to achieve at low scales, therefore inducing major errors when analysing instrumented indentation data.

In the case of sharp indenters, which are widely used for the evaluation of elastic modulus and hardness due to their geometrical self-similarity, Oliver and Pharr [1] suggested a since widely-used area function to take account of indenter bluntness in the case of a Berkovitch 3-sided pyramid, expressed by the following equation:

$$A_c = 24.5h_c^2 + \sum_{i=1}^{8} C_i h_c^{1/2^{(i-1)}} \quad (1)$$

with A_c the contact area, 24.5 the proportionality factor between A_c and the square of h_c in the case of an ideal Berkovitch indenter and C_i the additional factors which represent the bluntness of the indenter tip.

In the case of spherical indenters, which are very convenient for the evaluation of flow properties because they induce penetration depth-dependent stress–strain fields, the analysis of the indentation data is subject to a length scale, i.e. the indenter radius, and the data analysis methods do not rely on an area function. Research studies [22–24] on the calibration of the geometrical imperfections

* Corresponding author at: LGCGM, 20 Avenue des Buttes de Coësmes, 35708 Rennes Cedex, France. Tel.: +33 6 32 66 29 74.
E-mail address: philippe.brammer@univ-rennes1.fr (P. Brammer).

0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.01.028

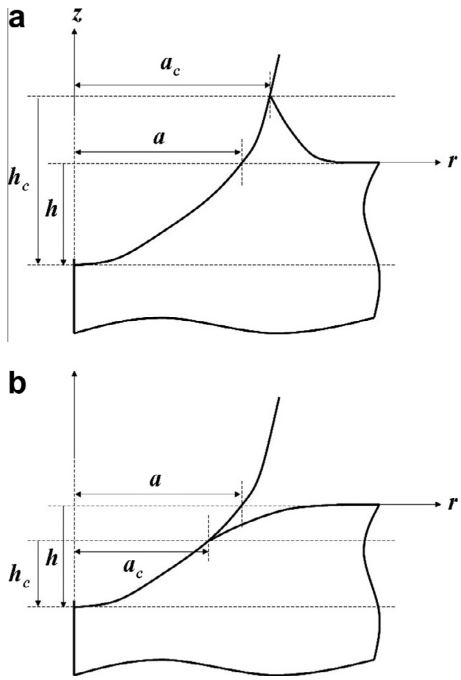

Fig. 1. Geometric values of interest in the cases of (a) pile-up and (b) sink-in.

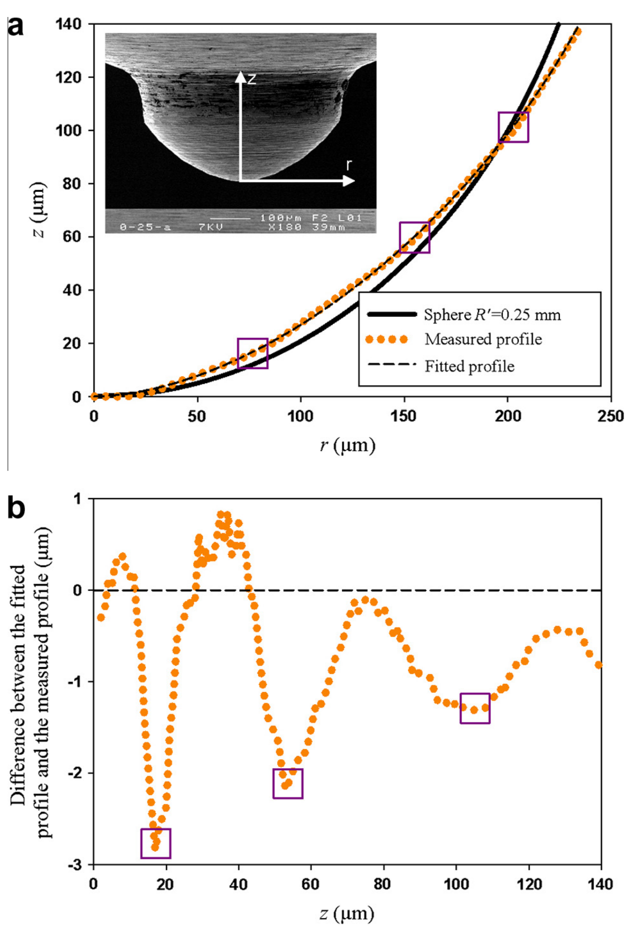

Fig. 2. (a) Measured indenter profile (Scanning Electronic Microscopy) and (b) difference between the fitted and the measured profile.

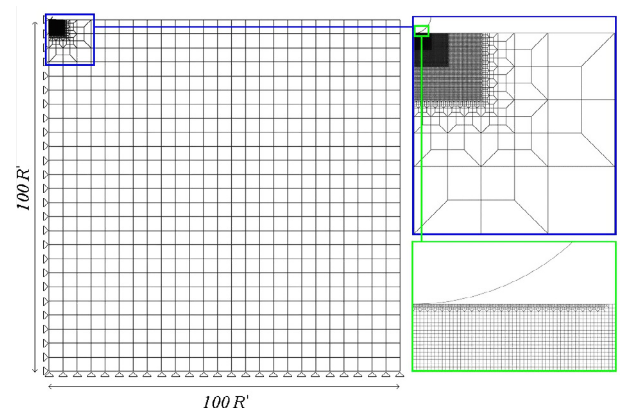

Fig. 3. Mesh used for the FEM simulations of indentation (case of the spherical profile).

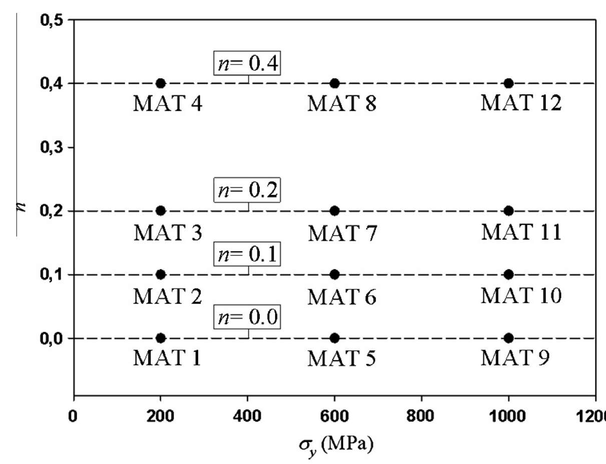

Fig. 4. Material parameter values used for the FEM simulations.

of spherical indenters used the profiling of the residual imprint by Atomic Force Microscopy to define an effective indenter radius R_{eff} as expressed by the following equation:

$$R_{eff} = \frac{a_c^2 + h_c^2}{2h_c} \tag{2}$$

The use of this effective radius significantly improved the results obtained by a representative stress-strain based method [23,24]. In the case of a reverse analysis model, Collin et al. [17,18,25] proposed an equivalent radius R_{eq} to correct the indentation curve obtained with a nonspherical indenter. However, this relation was obtained by fitting of numerical data and is only relevant for a particular indenter.

The present work aims at an increased understanding of which geometrical and physical quantities allow for the transformation of an indentation curve obtained with an imperfect spherical indenter into an indentation curve which would be obtained with an ideal spherical indenter. The main objective of this transformation is to allow the application of reverse analysis models based on ideal spherical geometry to indentation data obtained with imperfect indenter geometry. In Section 2, the effect of imperfect indenter geometry on numerical indentation curves obtained on twelve materials is brought out. In Section 3, two geometrical correction methods are assessed as well as the relevance of the use of the penetration data or the contact data. In Section 4, a reverse analysis model based on ideal spherical geometry is applied to ideal, initial, and corrected data to confirm the relevance of the proposed correction method.