International Journal of Mechanical Sciences 53 (2011) 471–478

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Determination of the Drucker–Prager parameters of polymers exhibiting pressure-sensitive plastic behaviour by depth-sensing indentation

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ARTICLE INFO

Article history:
Received 28 December 2009
Received in revised form
15 June 2010
Accepted 3 April 2011
Available online 14 April 2011

Keywords:
Depth-sensing indentation
Pressure-sensitive materials
Finite element modelling
Inverse analysis

ABSTRACT

This paper presents a method to determine the Drucker–Prager parameters of pressure-dependant elastic-perfectly plastic polymeric materials by means of the depth-sensing indentation technique. This is achieved via an inverse analysis of the load–displacement data resulting from two tests performed with Berkovich and spherical tips. The well-posedness and the effective range of application of the proposed method are carefully assessed first. Then the method is tested for two elasto-plastic materials with mild initial strain-hardening (HDPE and PMMA), and the results are compared to those measured using conventional tensile and compression tests. It is found that the pressure-sensitivity indices can be accurately predicted, while the yield stress predictions in tension and compression fall within the non-linear portion of the uniaxial stress–strain curves, i.e., inside the region where plastic deformation begins.

1. Introduction

Since the appearance of depth-sensing indentation, great efforts have been dedicated to interpret the load–displacement curves in order to extract the mechanical properties of the indented substrates. Unlike traditional tests, e.g., uniaxial tension and compression, determination of mechanical properties using depth-sensing indentation requires some previous knowledge of the material behaviour.

Regarding the determination of Young's modulus for elastic materials, there is already a widely accepted method developed by Oliver and Pharr [1]. However, many materials depart from the same initial assumptions; hence, specific corrections for the Oliver and Pharr method have been proposed for other cases, such as viscoelasticity [2], excessive plastic deformation [3,4], sharp indentation [5], superhard materials [6] and surfaces with residual stresses [7]. Especially, plastic behaviour is a more complex problem and there is a larger diversity of behaviours. For example, indentation methods have already been developed to characterize the yield response of isotropic [8–13] and anisotropic [14] materials, which respond to the Ramberg–Osgood law, semi-brittle elasto-plastic materials with crack formation during indentation [15], and multilayered composites [16].

The indentation responses of materials exhibiting hydrostatic pressure-sensitive plastic behaviour, as is the case of some ceramics [17,18], bulk metallic glasses [19,20] and polymers [21,22], have also been studied. In general, the plastic behaviour of such materials can be described by the Mohr–Coulomb and Drucker–Prager yield criteria [23–27]. The Drucker–Prager [28] yield criterion is a generalisation of Coulomb's law, which is suitable for soil mechanics where the shear stress required for simple slip is linearly dependant on the normal pressure acting on the slip surface. The Drucker–Prager yield criterion has been successfully used to describe the plastic behaviour of polymers [29]. For example, it explains the slip-line patterns formed around notch tips in epoxies under remote tension and compression [30]. Finite element analyses (FEA) of Berkovich and Vickers indentations of elastic–plastic solids obeying both the Mohr–Coulomb and Drucker–Prager criteria were performed by Giannakopoulos and Larson [18] and Vaidyanathan et al. [19] to study the indentation response of ceramics and bulk metallic glasses. They showed that the indentation depth at a given indentation load decreased with the pressure-sensitivity index of the material due to the enhancement of the mean contact pressure. Narasimhan [31] developed a set of analytical equations to calculate the stress and displacement fields of a tip pressing against a material that responds to the hydrostatic pressure-dependant Drucker–Prager yield criterion.

Despite the above-mentioned research, there is yet no established method to determine the properties of pressure-sensitive plastic materials from the load–displacement curves resulting from depth-sensing indentation tests. This work aims to contribute

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doi:10.1016/j.ijmecsci.2011.04.002