Available online at www.sciencedirect.com
SCIENCE DIRECT®
International Journal of Solids and Structures 43 (2006) 2014–2036
INTERNATIONAL JOURNAL OF SOLIDS and STRUCTURES
www.elsevier.com/locate/ijsolstr

Role of plasticity on indentation behavior: Relations between surface and subsurface responses

Ivindra Pane *, Eberhard Blank

Computational Materials Laboratory, Institute of Materials, Swiss Federal Institute of Technology, CH-1015 Lausanne, Switzerland

Received 9 December 2004
Available online 21 October 2005

Abstract

Surface and subsurface responses during frictionless indentation of elasto-plastic solids are investigated. Cases of monotonic and repeated loading are considered. It is shown that the role of plasticity parameters on indentation behavior cannot be well described in terms of surface response alone. It must be tied with subsurface response. In particular, the difference between the materials exhibiting isotropic hardening and that exhibiting kinematic hardening is less apparent when the force-displacement response and the deformed surface from the two are compared. Yet, it is quite apparent when subsurface response such as plastic strain, residual stress and plastic zone dimension are compared. An attempt has been made to characterize such surface and subsurface responses, for different plastic behavior, and to compare them with estimations obtained from analytical solutions.

Keywords: Substrate; Plasticity

1. Introduction

Many situations involving elasto-plastic contact behavior exist in manufacturing, fabrication, and packaging processes, as well as in structural and mechanical systems. Elasto-plastic contact behavior also plays a key role in damage modes involving wear and friction often occurring in the above processes and systems. However, in the examples above the contact loading is seldom described by quantities derived from elasto-plastic contact behavior. Rather, contact loading and the material response at the surface are treated empirically in terms of hardness or indentation strain. The latter may represent the averaged material behavior but may not capture the important mechanisms responsible for material failures.

Although a number of studies have been dedicated to analyzing elasto-plastic indentation, the quantification of some representative surface and subsurface responses is not an easy task. In the early 1950s, based on the work of Meyer (1908) and Tabor (1951) substantiated quantities like hardness and indentation strain. These are surface responses that are believed to represent the material response involving elasto-plastic

* Corresponding author.
E-mail addresses: ivindra.pane@epfl.ch, ivpane@netscape.net (I. Pane).

0020-7683/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijsolstr.2005.08.010

indentation. Tabor's study and more recent studies (Park and Pharr, 2004; Mesarovic and Fleck, 1999; Yu and Blanchard, 1996) also imply that plastic and hardening behavior may not be well captured simply by surface response like a single-valued hardness, instead by hardness-indentation strain relations. Such relations obtained from spherical indentation have been shown to capture differences caused by different plastic and hardening behavior (Tabor, 1951; Tirupataiah and Sundararajan, 1991). This has been the basis for a method to infer the stress–strain relation of metallic materials (Tabor, 1951; Tirupataiah and Sundararajan, 1991, 1987, 1994). However, such a method is subject to some criticisms mainly due to the inaccuracy of the measured contact radius, and it has not been applied for a wide variety of elasto-plastic materials. Nevertheless, it is important to understand thoroughly the relation between hardness and indentation strain for materials with different hardening and plastic behavior. One way to do this is using the finite element simulation where the contact radius developing during indentation can be monitored accurately.

Since many technologically important materials including steels, cemented carbide, aluminum, copper, nickel, and their alloys exhibit different hardening behavior it appears necessary to study indentation responses as affected by hardening. This means that phenomena exhibited by the kinematic hardening such as Bauschinger effect and ratchetting, in addition to the classical isotropic hardening behavior, need to be investigated. Furthermore, to capture the complex effect of kinematic hardening, the investigation must be extended to the case of cyclic indentation loading. Indentation responses to be analyzed also need to be broadened to include, not only the surface response such as hardness-indentation strain, but also the subsurface response such as distributions and development of plastic strains, stresses, and plastic zone. While many investigations have been done to study the surface response by indentation (Tabor, 1951; Park and Pharr, 2004; Tirupataiah and Sundararajan, 1991, 1987, 1994; Jayaraman et al., 1998; Bhattacharya and Nix, 1988), very little is known about the subsurface response. This is not surprising because the indentation experiment measures only the surface response in terms of the load–displacement curve and the deformed surface profile. Some studies on the subsurface response have shed some light on the stress and strain distributions as well as on the size or shape of plastic zone (Hardy et al., 1971; Kral et al., 1993; Samuels and Mulhearn, 1956; Koeppel and Subhash, 1999). Since correlations between the surface and subsurface responses are still lacking, our intent here is to elaborate on such correlations and to see whether some important links can be made.

Capturing and modeling different hardening behavior at the continuum level remains a non-exhausted subject of research. Models have been developed to incorporate cyclic plasticity behavior which, according to Suresh (1998) should include the Bauschinger effect, elastic shakedown, cyclic hardening or softening, ratchetting, and mean stress relaxation (Armstrong and Frederick, 1966; White et al., 1990; Bower, 1989; Jiang and Sehitoglu, 1996,a,b; Mizuno et al., 2000; Ohno and Abdel-Karim, 2000; Ekh et al., 2000). Some of these models are very versatile and capture the aforementioned behavior. Many have been extended from a known kinematic hardening model by Armstrong and Frederick (1966). Evaluation of different hardening models is beyond the scope of this paper. Here, we limit our effort to elasto-plastic indentation simulations using a J_2-flow plasticity model with combined isotropic–kinematic hardening that enable us to capture Bauschinger effect, ratchetting and shakedown. Such a model has been presented and used by, among others, White et al. (1990), Ekh et al. (2000), and Pedersen (2000) for problems other than indentation. It appears to be satisfactory and capable of capturing the important aspects of cyclic hardening behavior.

It is worth mentioning that while there have been studies using the isotropic hardening plasticity (Bhattacharya and Nix, 1988; Kral et al., 1993), applications of cyclic hardening plasticity, and in particular using the combined isotropic–kinematic hardening to elasto-plastic contact problems are still rare. Investigations on how the isotropic and kinematic hardening models affect the spherical indentation behavior have been done by Huber and Tsakmakis (1998, 1999a,b) who emphasized more on extracting material properties but included some analysis on surface and subsurface responses.

This paper aims at studying the normal frictionless indentation behavior of homogeneous metallic substrates as influenced by their elasto-plastic parameters, and by no means covers all aspects related to constitutive modeling of materials and elasto-plastic indentation behavior. It focuses on studying some characteristic surface response due to spherical indentation, such as the variation of mean pressure (Meyer hardness) with indentation strain, and its relation to the subsurface response including the plastic zone dimension, plastic strain and residual stress. This is done primarily for the case of monotonic loading, where the role of plasticity parameters of different hardening behavior can be generalized and examined. Then, an analysis