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On the determination of the anisotropic plasticity of metal materials by using instrumented indentation

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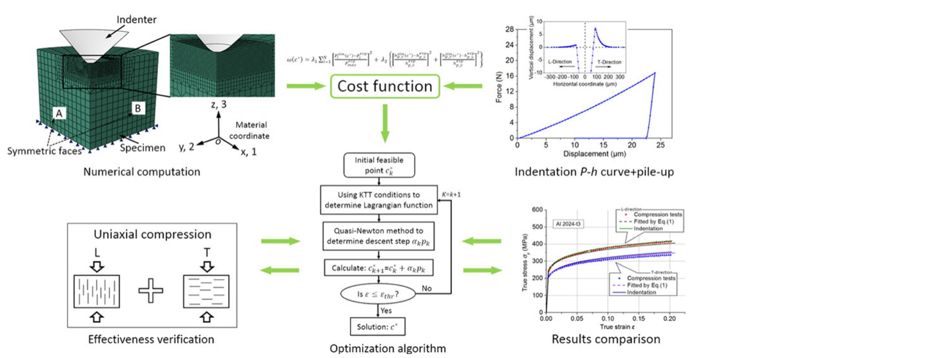
HIGHLIGHTS

- A new method is proposed to estimate the anisotropic plasticity of metal materials by using instrumented indentation.
- The ill-posed nature of using only the indentation *P-h* curve in the inverse analysis process is investigated.
- By introducing the pile-up effects, the well-posed solution is obtained.
- Effectiveness of the new approach is verified by application on two engineering materials.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, an inverse computation approach is proposed to estimate the anisotropic plastic properties of materials by using the instrumented indentation. For the anisotropic materials considered in the present study, the plastic properties (e.g. the stress strain curves) along orthogonal directions (e.g. longitudinal vs. transverse) are different. This approach is based on weighting the information collected from instrumented indentation and the conventional optimization algorithm. The ill-posed nature of using only the indentation load-displacement curve in the inverse analysis process is investigated. To obtain a unique solution, the pile-up values around indenter are considered as important additional information. Results show that, by introducing the pile-up values, the inverse analysis gives well-posed solution of the anisotropic plastic properties. The new approach is applied on two metal materials, and the anisotropic properties obtained from indentation and uniaxial tests show good agreement.

1. Introduction

In the natural and synthetic material systems, anisotropic materials are often observed and widely used in the industrial products, such as woods, composites, rolled sheets and so on. For the metal products made by pressure forming, the material plastic anisotropy has non-negligible influence on their final shapes, e.g. the in-plane anisotropic plasticity is related to the tendency of rolled sheets to form "ears" during drawing [1,2]. Besides, some metal matrix composites also show plastic anisotropy, e.g. the 15 vol.% SiC whiskers reinforced Al 2124 alloys, because of the aligned whiskers along one specific direction [3]. To accurately simulate the deformation behavior of materials and provide useful guidance for the technology design in metal plastic forming industry, numerous plasticity models have been proposed in past decades, especially for the anisotropic materials [4,5]. However, it is still an essential problem to the accurate determination of the plastic anisotropy

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of materials, so that these plasticity models can be effectively used. Traditionally, the plastic anisotropy of materials is analyzed by conducting uniaxial tests on the strip specimens along different angles from one direction. However, this test method is destructive and not suitable for in situ micro-testing. With the rapid development of micro-structure manufacturing industry and the need of material property evaluation, a versatile method which can be used to determine the material anisotropy in such conditions is of significance.

In the past few years, instrumented indentation test was widely used in the determination of various mechanical properties of materials, such as elastic modulus [6], elastoplastic properties of isotropic materials [7,8], residual stresses [9,10], fracture toughness [11,12], as well as the material anisotropy [13,14]. Perhaps, indentation test can be used as the substitute for the traditional uniaxial experiment, because this test approach is especially suitable for in situ micro-testing [14,15].

Vlassak and Nix [13] investigated the elastic anisotropy of materials, and revealed the "averaged" elastic effects under indentation, while the plastic anisotropy was not mentioned. Bocciarelli et al. [16] used indentation test to calibrate the anisotropic parameters of Hill's plasticity model. In Ref. [16], both the elastic and plastic anisotropic parameters were considered, however the theoretical analysis process was complex. In indentation studies, the complexity of the inverse computation model and the uniqueness of the inverse identified set of parameters are two major challenges, which determine the practical usefulness of such techniques [17]. On this issue, generally two aspects were considered in the previous researches.

On the one hand, many methods were proposed to simplify the analysis process or to reduce the computation burden, such as the utilization of the concept of representative strain [7,15] or the model reduction strategy [18]. In Ref. [15], the concept of representative strain, originally proposed in conical indentation for isotropic materials [7], was successfully extended to spherical indentation of anisotropic materials. Based on this, Yonezu et al. [15] established a series of dimensionless functions to extract the anisotropic plasticity of materials. Bolzon and Talassi [18] proposed an inverse analysis tool to extract the elastoplasticity of anisotropic materials. In this tool, computation burden of the analysis process was greatly reduced by using the proper orthogonal decomposition and radial basis functions approximation.

On the other hand, the additional experimental information was used to alleviate the non-uniqueness problem in the inverse analysis process [14,19–25], such as the utilization of the dual indenters or the residual surface deformation (e.g. pile-up/sinking-in effects). Nakamura and Gu [19] used both the Berkovich and spherical indenters to extract the anisotropic elastoplasticity of thermally sprayed coatings. In Ref. [19], they found the *P-h* curves from these two indenters exhibit opposite behaviors as the modulus ratio changes. Besides, they observed the size and anisotropic effects. Kalkhoran et al. [14] proposed an indentation-based technique to quantify the extent of material plastic anisotropy. This technique relies on the observation of the shape of strain field along the free edge of specimen after indenter withdrawal, however the experimental procedure is tedious.

Surface deformation has long been used as the important material response in indentation experiment [20–25]. For isotropic materials, the pile-up effect was used as the supplementary information of *P-h* curve to solve the non-uniqueness (or duality) problem of the inverse identified set of material parameters [20–22]. For crystal plasticity, the surface pile-up distribution was strongly dependent on the crystal orientation, and it was used as the "fingerprint" to help to understand the underlying crystal deformation mechanisms [23–25]. Besides, the pile-up patterns were also used to the identification of the anisotropic parameters of materials, with the assistance of finite element simulation using crystal plasticity [26,27]. However, crystal plasticity model usually involves a large number of material parameters, which complicates greatly the extraction of the material properties using inverse analysis [24].

This paper is the investigation on the determination of the anisotropic plasticity of metal materials, by properly weighting the information collected from instrumented indentation. The study shows the ill-posed nature of inverse analysis when only the indentation *P-h* curve is used to the identification of the anisotropic plasticity of metal materials, and the inverse analysis will become well-posed when the pile-up effects of materials are properly considered. The new method calls for single indentation test and it does not involve the complicated fitting functions. The present study is organized as follows. Material model, numerical computation model, and inverse analysis tool are presented in Section 2. Uniaxial compression and indentation experimental investigations on two real anisotropic materials are presented in Section 3. The results and discussion are presented in Section 4. Conclusions are summarized in Section 5.

2. Basic methods

2.1. Computation models and results

2.1.1. Material model

To describe the plastic deformation behavior of anisotropic materials, Hill's plasticity theory [28] is used for its relatively simple form and the anisotropic constants are easy to be defined through experiments. The six yield stress ratios R_{11}, R_{22}, R_{33}, R_{12}, R_{13} and R_{23} in respectively three normal (R_{11}, R_{22} and R_{33}) and three shear (R_{12}, R_{13} and R_{23}) directions are used to quantify the orthogonal anisotropic plasticity, as shown in Fig. 1. These six anisotropic constants are inputted by using

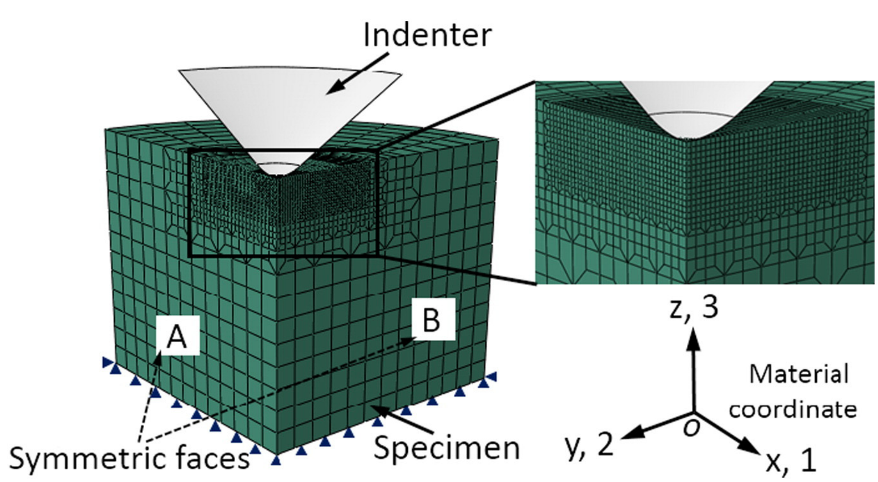

Fig. 1. The material model, finite element model, meshes, boundary conditions and material coordinate used in the indentation simulation.