International Journal of Plasticity xxx (2016) 1–22

Contents lists available at ScienceDirect

International Journal of Plasticity

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

Application of the virtual fields method to the identification of the homogeneous anisotropic hardening parameters for advanced high strength steels

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A R T I C L E I N F O

Article history:
Received 15 April 2016
Received in revised form 21 July 2016
Available online xxx

Keywords:
B. Constitutive behaviour
B. Metallic material
C. Finite elements
C. Mechanical testing
Constitutive parameters identification

A B S T R A C T

In the present paper, an inverse problem solution so called the virtual fields method (VFM) is implemented to identify the parameters of the homogeneous anisotropic hardening (HAH) model, a distortional plasticity-based model that describes the material plastic behavior when subjected to strain path changes. The framework of the identification method that combines the formulation of the yield condition, the constitutive stress–strain relation and the principle of virtual work is presented. For validation purpose, the proposed identification method was first attempted on finite element (FE) generated data for a forward-reverse simple shear test to investigate its capability in retrieving the input constitutive parameters. The influence of noise was also evaluated. Then, the identification method was applied to a selection of advanced high strength steel (AHSS), namely DP600, TRIP780 and TWIP980, sheet specimens, subjected to a small number of forward-reverse simple shear cycles. The material constitutive parameters were identified using the VFM based on which shear stress–strain curves were calculated and compared with their experimental counterparts. Good agreement was found between the calculated and the experimental curves despite the larger discrepancies observed in the reverse loading paths. To adjust these discrepancies, the original HAH model was modified with respect to the permanent softening related state variables. After modification, the model was simplified with only one state variable related to permanent softening. It was found that the discrepancies observed in the reverse loading paths were reduced with the modified HAH model.

1. Introduction

Advanced high strength steels (AHSS) are widely used in the automotive industry due to their superior strength while maintaining high tensile elongation. Depending on the different requirements of automotive parts, e.g., crash worthiness, stiffness, lightweight, various types of AHSS can be chosen, such as dual-phase (DP), transformation-induced plasticity (TRIP) and twinning-induced plasticity (TWIP) steels. These steels exhibit various strength and maximum tensile elongation capabilities primarily due to different volume fractions of ferrite, martensite, bainite and austenite phases. During sheet metal

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http://dx.doi.org/10.1016/j.ijplas.2016.07.013
0749-6419/

Please cite this article in press as: Fu, J., et al., Application of the virtual fields method to the identification of the homogeneous anisotropic hardening parameters for advanced high strength steels, International Journal of Plasticity (2016), http://dx.doi.org/10.1016/j.ijplas.2016.07.013

forming, it is often challenging to achieve the desired shape with these materials since they generally exhibit lower ductility and larger elastic recovery, which, as a consequence, lead to the undesired springback phenomenon when forming loads are released (Firat et al., 2008; Haddag et al., 2007; Lee et al., 2005b; Yanagimoto et al., 2005).

As is well known, the Bauschinger effect and permanent softening play an important role in the springback phenomenon. The former corresponds to the decrease in reloading yield stress after a load reversal while the latter is related to the inability to recover the flow stress level of isotropic hardening. Efforts have been dedicated by many researchers to capturing these effects since isotropic hardening, which assumes that the yield surface expands proportionally, is not sufficient anymore for the prediction of springback, particularly using AHSS. Kinematic hardening models have been verified to be able to capture the Bauschinger effect and permanent softening as reviewed in (Chaboche, 2008). Various kinematic hardening models have been developed so far, from the early form that assumes that the yield surface translates in specific directions in the stress space while its shape is maintained (Prager, 1949; Ziegler, 1959), to the non-linear kinematic hardening models that combine both translation and expansion of the yield surface (Chaboche, 1986; Dafalias and Popov, 1975; Frederick and Armstrong, 2007; Ohno and Wang, 1993) and, more recently, the models that account for plastic anisotropy (Chung et al., 2005; Geng and Wagoner, 2002; Lee et al., 2005a,b; Yoshida et al., 2015; Yoshida and Uemori, 2003). Alternatively, the distortional plasticity-based constitutive model denoted 'homogeneous anisotropic hardening (HAH)' (Barlat et al., 2011) can be used to capture these effects. Unlike the translation of the yield surface in kinematic hardening, the HAH model assumes that the yield surface both flattens on the opposite side of the active stress locus and isotropically expands (Manopulo et al., 2015). This model has advantages that it is expressed with a homogeneous function of degree one and reduces to isotropic hardening (with either an expanding isotropic or anisotropic yield surface) when the material is subjected to monotonic loading. This is a more realistic representation of material plastic behavior in practice. The finite element (FE) implementation of the HAH model has been successfully achieved by Lee et al. (2012), which is a useful tool to predict springback in metal forming. Very recently, the HAH model was extended to cross-loading cases with consideration of latent hardening effects (Barlat et al., 2013). It has also been refined to predict the mechanical response of metals subjected to non-proportional loading conditions (Barlat et al., 2014).

Increasing complexity in material models generally means that their experimental identification requires larger numbers of simple statically determinate tests. This is inconvenient and expensive, not even mentioning the issue related to obtaining the nominal target stress state because of inadequate boundary conditions and/or localization effects. With the strong development of strain mapping technology like digital image correlation (DIC) (Sutton et al., 2009), alternatives based on more complex test configurations have emerged. However, the static determination is generally lost in these, meaning that effective inverse tools are required to extract the constitutive parameters from the strain maps. Finite element model updating (FEMU) is a widely accepted inverse solution tool as reviewed in (Avril et al., 2008). It basically determines the material parameters by minimizing the discrepancy between FE simulation results and the experimental measurements. This has been applied over the years to a wide range of constitutive models, among which elasticity and elasto-plasticity (Broggiato et al., 2008; Güner et al., 2012; Lecompte et al., 2007; Wang et al., 2011; Zang et al., 2014; Zhang et al., 2014). Nevertheless, FEMU is computationally demanding since a FE model has to be updated iteratively, even for the simplest case of elasticity. An alternative is to use the virtual fields method (VFM) (Pierron and Grédiac, 2012), an efficient inverse solution tool which is based on the principle of virtual work and takes full advantage of the availability of deformation maps through techniques such as DIC or the grid method (Grédiac et al., 2016), for instance. This approach determines the material parameters by minimizing the gap between the total internal and external virtual works (IVW and EVW) during the whole deformation process. The identification procedure is usually implemented using a simple MATLAB® program[1] and is very computationally efficient. So far, the VFM has been applied to elasticity, hyperelasticity, plasticity, and viscoplastictiy, for the characterization of various materials (Fu et al., 2013; Grama et al., 2015; Grédiac and Pierron, 2006; Kim et al., 2012; Pierron et al., 2010). More work still needs to be done to extend the application of this method.

Currently, the identification of the HAH parameters is based on the FEMU approach in which the FE predicted stress–strain curve is updated iteratively to fit its experimental counterpart as done in (Choi et al., 2015). However, for the simple case of only one reverse loading path, this process generally takes a few days depending on the initial estimate as well as the deformation history. For more reverse loading cycles, the computation time is likely to be substantially longer. Therefore, it is highly desirable to develop a more efficient method to identify the HAH parameters.

In the present study, the VFM is extended to accommodate the HAH model. The proposed identification method is applied to the selected AHSS to identify their constitutive parameters when subjected to a few loading cycles. In Sections 2 and 3, the identification methodology is introduced step by step through an outline of the HAH formulation, the stress–strain constitutive relation and the principle of the VFM. In Section 4, the proposed identification method is validated on FE-generated data. The choice of virtual fields and the influence of measurement noise are also discussed. In Section 5, the proposed identification method is applied to experimental data from which the HAH parameters are identified for the selected AHSS. In Section 6, based on a discussion pertaining to the identification results, the original HAH model is modified to better describe the experimental response.

[1] A commercial software platform integrating DIC and VFM is now available, www.matchidmbc.com.

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