International Journal of Plasticity 46 (2013) 130–142

Contents lists available at SciVerse ScienceDirect

International Journal of Plasticity

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

Extension of homogeneous anisotropic hardening model to cross-loading with latent effects

Frédéric Barlat [a,b], Jinjin Ha [a], José J. Grácio [b], Myoung-Gyu Lee [a,*], Edgar F. Rauch [c], Gabriela Vincze [b]

[a] Graduate Institute of Ferrous Technology (GIFT), Pohang University of Science and Technology (POSTECH), San 31 Hyoja-dong, Nam-gu, Pohang, Gyeongbuk 790-784, Republic of Korea

[b] Center for Mechanical Technology and Automation, Mechanical Engineering Department, University of Aveiro, 3810 Aveiro, Portugal

[c] Science et Ingénierie des Matériaux et des Procédés, Groupe GPM2 (CNRS UMR 5266) INPG-UJF, BP 46, 38402 Saint Martin d'Hères CEDEX, France

ARTICLE INFO

Article history:
Received 4 May 2012
Received in final revised form 6 July 2012
Available online 31 July 2012

Keywords:
A. Dislocations
A. Latent hardening
B. Yield condition
B. Strain hardening
B. Constitutive behavior

ABSTRACT

The homogeneous anisotropic hardening (HAH) approach, which captures the Bauschinger effect in metallic materials effectively during load reversal, was extended to cross-loading cases with latent hardening effects. This continuum approach is based on the physical understanding of dislocation structure evolution during strain path changes but does not include the concept of kinematic hardening. The model was well validated for a deep drawing quality sheet sample. However, for a dual-phase steel, differences between predicted and experimental results were observed and discussed. Based on these results, additional validation tests and further improvement in the approach were suggested.

1. Introduction

Lightweighting for automotive body and structure components calls for materials with high specific strength such as light metal and advanced high strength steel (AHSS) sheets. However, these materials are challenging to form into engineered products because they generally do not exhibit good ductility at room temperature. Moreover, the low elastic modulus of the former and the very high strength of the latter contribute to large elastic material recovery and part distortion, i.e., to springback, when forming loads are removed. In order to predict this phenomenon, numerical methods have been developed (e.g., Lee et al., 2005, 2007; Banu et al., 2006; Oliveira et al., 2007; Vladimirov et al., 2010; Yoshida, 2010) with the ultimate goal of controlling the geometrical and dimensional features of a part within a prescribed tolerance.

Since the Bauschinger effect has a strong influence on springback simulation results, it should be accounted for by the constitutive description. Non-linear kinematic hardening has been an effective approach to model this effect (see Chaboche, 2008, for a review) and was specifically adapted to sheet forming applications (Yoshida et al., 2002; Yoshida and Uemori, 2002, 2003). Teodosiu and Hu (1998) and Haddadi et al. (2006) combined kinematic hardening with a tensorial description of dislocation structures developing during load reversal or any possible strain path changes to better account for microscopic changes occurring during plastic deformation. This and similar methods were incorporated in crystal plasticity models to explicitly describe the behavior of individual slip systems and their interactions (Peeters et al., 2000; 2001a,b; Li et al., 2003; Mahesh et al., 2004; Beyerlein and Tomé, 2007; Holmedal et al., 2008; Franz et al., 2009). In a simpler approach, Takahashi and Shiono (1991) proposed to describe the one-dimensional Bauschinger effect using the backlash model, i.e., a delay in the mechanical response due to Orowan loops interactions. From a different viewpoint, yet based on experimental

* Corresponding author. Tel.: +82 54 279 9022; fax: +82 54 279 9299.
E-mail addresses: f.barlat@postech.ac.kr (F. Barlat), mglee@postech.ac.kr (M.-G. Lee).

0749-6419/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijplas.2012.07.002

evidence (Vincze et al., 2005), Rauch et al. (2007, 2011) suggested to represent the dislocation microstructure by only three variables associated with dislocation densities in order to describe the stress–strain behavior for a single strain path change.

In order to extend this simpler approach to strain paths with multiple or continuous changes, a distortional hardening model, called HAH, was proposed in a previous investigation (Barlat et al., 2011). Although this model is able to describe the Bauschinger effect in metals, it is not based on kinematic hardening but on a homogeneous yield function defined by a stable component, associated with an isotropic or anisotropic yield function, and a fluctuating component, which distorts the overall yield surface shape. However, the rapidly fluctuating component does not change the yield surface shape near the active stress state for proportional loading. Thus, for this particular case, HAH leads to a plastic response identical to that predicted using isotropic hardening. The HAH model was successfully implemented in the finite element (FE) code ABAQUS and used to compute springback in the U-draw bending process (Lee et al., 2012, in press-a) for as-received and pre-stretched advanced high strength steel (AHSS) blanks. The springback angles associated with the die and blank-holder radii as well as the specimen side-wall curl predicted with this FE analysis were in reasonably good agreement with the experiments.

Although the HAH model is able to describe the plastic flow behavior for any arbitrary and complex deformation path, it was developed to specifically capture the material behavior after a load reversal. However, there is a wide range of possible strain path change between monotonic reloading and complete reversal. Most of this range can be investigated using a two-step tension test, in which the second tensile loading step is conducted at an angle ξ with respect to the first. For a number of materials, the flow stress after reloading may, depending on ξ, overshoot the monotonic stress–strain curve (Raphanel et al., 1989). The degree of overshooting, which depends on the severity of the strain path change, is usually maximum for an angle ξ of about 60°. This corresponds to so-called cross-loading in which all the slip systems active during the second step were inactive in the first. The degree of overshooting was explained at a microstructural scale in terms of latent effect resulting from the interaction between the newly active systems of the second step and the dislocation structure built-up of the first step, as shown in Schmitt et al. (1991) and discussed in Barlat et al. (2003a). Macroscopically, kinematic hardening, for which the reloading flow stress is inherently lower than that at unloading, is not likely to provide an acceptable constitutive description of this phenomenon.

The purpose of this article is to incorporate latent hardening effects in the HAH model during cross-loading, i.e., when new slip systems are activated after a strain path change, and to validate the model for two-step tension tests with various angles between the two loading directions. In Section 2, the main features of the formulation are reviewed, including the dislocation density-based hardening model (Rauch et al., 2007). Section 3 describes the model extension by Rauch et al. (2011), which allows the reloading flow stress to overshoot the monotonic strain hardening curve for cross-loading conditions, and its adaptation to HAH. In addition, Section 3 provides a summary of the equations needed in the HAH approach and a brief description of the material coefficient identification. In Section 4, a few illustration examples using the HAH model are presented. In particular, for EDDQ and DP780 steel sheet samples, experimental and predicted stress–strain curves determined during a selection of two-step tension tests are compared and discussed.

2. HAH formulation

2.1. General framework

In this paper, only the constitutive modeling of plasticity itself is described in a small deformation (incremental plasticity) framework. The associated flow rule is assumed to be a good approximation of the material behavior, which is reasonable for metals. The model can be combined with an appropriate elastic behavior using the additive decomposition. For instance, this model was implemented in a finite element (FE) code with Hooke's law (Lee et al., 2012) or with a non-linear dissipative elastic behavior (Lee et al., in press-b) without any major issues. Large deformation and objectivity result from the use of a co-rotational reference frame that closely follows the material symmetry axes. This approximation is satisfactory when shear strains are not too excessive.

2.2. Yield function

The HAH approach is based on a yield function $\bar{\sigma}(\mathbf{s})$, which also serves as a plastic potential,

$$\bar{\sigma}(\mathbf{s}) = \left[\phi^q(\mathbf{s}) + f_1^q|\hat{\mathbf{h}} : \mathbf{s} - |\hat{\mathbf{h}} : \mathbf{s}||^q + f_2^q|\hat{\mathbf{h}} : \mathbf{s} + |\hat{\mathbf{h}} : \mathbf{s}||^q\right]^{\frac{1}{q}} = \sigma(\bar{\varepsilon}) \quad (1)$$

where: denotes the double dot product, $\mathbf{s}$ is the stress deviator and q a constant exponent (Barlat et al., 2011). $\phi(\mathbf{s})$, the stable yield function component, and $\bar{\sigma}(\mathbf{s})$ are both homogeneous of first degree. $\hat{\mathbf{h}}$ is a normalized tensorial state variable, the microstructure deviator, which represents the microstructure evolution during the material loading history. Its initial value $\hat{\mathbf{h}}^{\mathbf{o}}$ is that corresponding to the normalized stress deviator $\mathbf{s}^{\mathbf{o}}$ leading the first increment of plastic deformation, i.e.,

$$\hat{h}_{ij}^o = \frac{s_{ij}^o}{\sqrt{\frac{8}{3}s_{ij}^o s_{ij}^o}} \quad (2)$$