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Enhancements of homogenous anisotropic hardening model and application to mild and dual-phase steels

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ABSTRACT

The formulation of the so-called homogeneous anisotropic hardening (HAH) model, which was originally proposed in Barlat et al. (2011), is refined. With the new features, this distortional plasticity-based constitutive model predicts the mechanical response of metals subjected to non-proportional loading with improved accuracy, in particular for cross-loading. In that case, applications to two different steels are provided for illustration purposes. For mild steel, the stress overshoot of the monotonic flow curve observed during a double load change is well reproduced by the model. In addition, for a dual-phase steel deformed in a two-step tension test with axes at 45° from each other, the new features allow the reloading yield stress to be lower than the unloading flow stress, in good agreement with experimental observations.

1. Introduction

Metal processing, part manufacturing and component service performance usually involve moderate to large amounts of plastic deformation. Depending on the details necessary for a particular application, metal plasticity is employed at scales ranging from groups of atoms to continuum. However, it is most efficient to adjust the scale of an investigation to that of the application, whether it is of fundamental nature or more practical. The present work deals with the continuum description of plasticity because, for the time being, this scale level more efficiently contributes to the solution of large forming problems. Needless to say that contributions at all finer scales are essential for the understanding of plasticity and for the development of material nano- and micro-structures allowing the improvement of plastic properties. Thus, an ideal continuum plasticity model should capture, at least in an approximate way, some of the lower scale features that dictate the mechanical behavior at a higher scale. In this article, the constitutive modeling of plasticity is considered within this context, particularly but not exclusively for sheet forming applications. Moreover, the scope of this work is restricted to elements of the classical theory of plasticity, namely a yield surface, which is also a plastic potential, evolving as a function of the specific plastic work or an associated measure of accumulated strain.

The simplest approach considers an expanding isotropic yield surface. Among many important contributions, the yield conditions of Hershey (1954), Hosford (1972) and Karafillis and Boyce (1993), expressed with principal stresses, are the most relevant to the present work for isotropic materials. However, studies conducted over several decades have demonstrated that plastic anisotropy has a strong influence on the results of numerical forming process simulations. The pioneering works

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of von Mises (1928) and Hill (1948) have paved the way for further investigations in the topic of anisotropic yield functions associated with isotropic hardening. Banabic et al. (2010) published a review about this topic. The development of anisotropic yield functions has motivated a large number of researchers such as Hill (1979), Logan and Hosford (1980), Barlat and Lian (1989), Barlat et al. (1991), Karafillis and Boyce (1993). A next generation of advanced yield functions, allowing a finer description of plastic anisotropy, was developed at the expense of additional coefficients as, for instance, by Barlat et al. (2003a, 2005), Bron and Besson (2004), Cazacu and Barlat (2004), Cazacu et al. (2006), Soare et al. (2008) and more recently by Yoshida et al. (2013) and Aretz and Barlat (2013). Some of the non-quadratic yield functions lead to results that compare well with crystal plasticity calculations and contain, in a sketchy way, information about the material structure. Advanced experimental techniques based on multiaxial loading, e.g. Kuwabara (2013), were developed to test these proposals very carefully and to extract relevant coefficients that cannot be determined in uniaxial loading. Finite element (FE) simulations of forming gained in accuracy with the advent of these more advanced yield functions (e.g. Yoon et al., 2004, 2006).

Nevertheless, isotropic hardening is too simple to provide a sufficiently accurate description of the real behavior of materials. For instance, the Bauschinger effect, which corresponds to a lower reloading yield stress followed by a high rate of strain hardening after load reversal such as tension–compression or torsion cycles, has entailed the development of anisotropic hardening theories. In particular, kinematic hardening (Prager, 1949; Ziegler, 1959), in which the yield surface shape is preserved but translates in stress space, has been able to capture the Bauschinger effect. Non-linear kinematic hardening theories based on one (e.g. Armstrong and Frederick, 1966) or multiple (e.g. Mroz, 1967; Dafalias and Popov, 1975; Krieg, 1975) yield surfaces are essential to describe phenomena that occur in metals subjected to cyclic loading. A number of these approaches were reviewed recently by Chaboche (2008) and discussed further by Xiao et al. (2013). Kinematic hardening has been found to be important for sheet forming simulations as well because the Bauschinger effect influences springback. In a recent review, Wagoner et al. (2013) discussed the features that most affect springback predictions and concluded that it is essential to consider the Bauschinger effect and permanent softening to predict springback accurately. The latest kinematic hardening theories have been able to capture these phenomena effectively (Yoshida and Uemori, 2002, 2003; Yoshida et al., 2002; Chung et al., 2005; Lee et al., 2005, 2007).

Alternatively, anisotropic strain hardening effects have been described using distortional plasticity approaches as, for instance, proposed by Ortiz and Popov (1983), Voyiadjis and Foroozesh (1990), Feigenbaum and Dafalias (2007, 2008), Dafalias and Feigenbaum (2011), or more recently by Shutov and Ihlemann (2012). In this case, the yield surface does not preserve its shape during plastic deformation. Distortional plasticity models are often used in association with other hardening rules. For instance, Kurtyka and Życzkowski (1996) proposed a hardening law transforming the yield surface through expansion, translation, distortion and rotation. These theories are useful, in particular for the description of the yield surfaces measured on the basis of the proportional limit as in Phillips et al. (1972) or for a very small offset strain of the order of 10^{-5}, as discussed by Khan et al. (2009), because these surfaces tend to display great amounts of distortion. However, these theories are difficult to use in forming process simulations unless the distortion is associated to differential hardening, such as in Aretz (2008), which does not account for load reversal or other form of complex loading.

Isotropic hardening theories are usually accurate enough for proportional loading but fail when loading changes during plastic deformation. Reverse loading, such as forward–reverse simple shear, is the most drastic change but any sequence with abrupt or smoothly changing load may be considered. Sequences of two non-coaxial loads, such as uniaxial tension in different directions or tension followed by simple shear, have been investigated. Uniaxial tension in three directions, i.e., with two successive load changes, were also performed by Kim and Yin (1997). Many of the experiments that involve one single load change have been mostly performed on low carbon steel (Raphanel et al., 1989; Hu et al., 1992) or aluminum alloys (Lopes et al., 2003; Barlat et al., 2003b). Dislocation density-based models for non-proportional loading were develop by Rauch et al. (2007, 2011) and incorporated into a crystal plasticity framework by Kitayama et al. (2013). Kinematic hardening-based models that account for dislocation structures were introduced by Hu et al. (1992), Teodosiu and Hu (1998), and extended in combination with crystallographic texture by Peeters et al. (2000, 2001) to capture the behavior of single-phase materials.

In addition, a number of two-phase materials such as advanced high strength steels (AHSS) have been investigated as well, in particular, dual-phase steels, which are more relevant to the present work. Modeling the non-proportional loading behavior of dual-phase steels has been carried out at microscopic scales, which allows the introduction of a number of microstructural parameters (Franz et al., 2009; Yoshida et al., 2011; Carvalho Resende et al., 2013). These models are powerful because they explicitly account for the mutual interactions between phases, grain boundaries and other microstructural features. However, they are not numerically efficient for simulations of large-scale forming processes. Continuum approaches have been used for the purpose of capturing the macroscopic behavior of DP steels (Tarigopula et al., 2008, 2009; Kuwabara and Nakajima, 2011; Chongthairungruang et al., 2012; Sun and Wagoner, 2013). In these models, the parameters do not describe explicitly the microstructure but the mechanical phenomena that occur during plastic deformation such as Bauschinger stress, transient hardening rate, latent hardening and permanent softening. Moreover, these approaches are efficient for forming simulations.

Recently, the present authors introduced the homogeneous anisotropic hardening (HAH) approach, which relies on a simple interpretation of the collective behavior of dislocations during plastic deformation (Barlat et al., 2011). It was first developed as an alternative to kinematic hardening to describe the Bauschinger effect. In fact, although very effective for this purpose, there is no reason to describe the Bauschinger effect exclusively using kinematic hardening. Therefore, unlike most of other theories, the concepts of back-stress and kinematic hardening are excluded from the HAH approach. However, elements of isotropic expansion, distortion and rotation of the yield surface are included. The HAH model was extended later