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Inherent and induced anisotropic finite visco-plasticity with applications to the forming of DC06 sheets

A. Behrouzi [a], C. Soyarslan [a,*], B. Klusemann [a], S. Bargmann [a,b]

[a] Institute of Continuum Mechanics and Material Mechanics, Hamburg University of Technology, Hamburg, Germany
[b] Institute of Materials Research, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany

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ABSTRACT

In the current work we present a finite visco-plasticity model accounting for inherent and induced plastic anisotropy as well as Bauschinger effect for the interstitial free (IF) steels and its application to a forming process simulation of DC06 sheets. The inherent plastic anisotropy uses a Hill-48 type structural tensor whereas the induced anisotropy is modeled via its evolution accounting for dynamic (active) and latent (inactive) parts. The latter appears to be an eminent requirement for predicting the qualitative effect of the evolving dislocation microstructures under orthogonal loading path changes, i.e., the cross hardening. A nonlinear isotropic and Armstrong–Frederick type kinematic hardening is also involved. Finally, the rate dependence of the plastic response is incorporated using Johnson–Cook type formulation. The model is implemented as VUMAT user defined material subroutine for ABAQUS and used in a set of sensitivity analyses to present mentioned model features. The model parameters are identified based on a set of experiments involving monotonic shear, uniaxial tension, forward to reverse shear and plane strain tension followed by shear tests. Finally, the channel forming process of a DC06 sheet is simulated. A good agreement with the experimental findings is observed, in both the tool response history curves and the extent of spring-back which is conclusive on the final product geometry.

1. Introduction

The macroscopic behavior of the polycrystalline metals is closely linked to the underlying microstructure and its evolution. Under sufficiently intense load levels, new dislocations nucleate in addition to the existing ones: they gain mobility and interact with barriers, e.g., grain boundaries, inclusions, solid solutions, as well as each other. The way how these interactions occur, depends on the loading history, i.e., the loading path being monotonic, reverse or, e.g., orthogonal. Under monotonic loading paths dislocations accumulate in front of barriers to form pile-ups. The consequent increase in the resistance to flow is referred to as strain hardening. Once the load is reversed at proceeding stages, the pile-ups are partially dissolved, with the dislocations departing from the barriers. This early re-yielding at load reversals is referred to as the Bauschinger effect [1]. On the other hand, if instead of a complete load reversal, an orthogonal loading is pursued, prevailing dislocations hinder the slip on the newly activated slip systems. Resultant latent resistance to yielding and hardening rate increase is named as cross hardening, see, e.g., Ghosh and Backofen [2] for one of the pioneering reports and Rauch and Schmitt [3] as well as Rauch and Thuillier [4] who reported dislocation microstructure alterations under tension followed by shear as subsequently orthogonal loading paths. Nesterova et al. [5] investigated the microstructure under two strain path changes (simple-shear/simple-shear and uniaxial-tension/simple-shear) in an interstitial free (IF) steel where the influence of the grain orientation is discussed as well. Gardey et al. [6] studied the dislocation structures in dual-phase steel under different loading paths, including orthogonal loading and the effect of the different strain paths on the dislocation structure is discussed in detail.

Mathematical modeling approaches associated with such micro-macro interactions differ by the scale at which the mathematical constructs and their emerging relations are formulated. The micro-scale based mechanistic approaches use mathematical entities in direct association with corresponding microstructural phenomena. Within the current context, glide-system level resolutions with crystal plasticity (e.g., [7–9] and for a recent overview see Roters et al. [10]) as well as gradient extended crystal plasticity [11–16] were presented. These approaches, while supplying higher accuracy with less approximations, require relatively high computational cost as compared to their phenomenological counterparts which base their formulations at the meso- or macroscale using smeared microstructural properties. Since the current work aims at simulation of a metal

* Corresponding author. Tel.: +49 40 42878 2562.
E-mail address: celal.soyarslan@tu-harburg.de (C. Soyarslan).

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forming process of DC06 steel sheets at the macroscale, a phenomenological modeling approach is adopted here.

The phenomenological approaches account for the micromechanical phenomena mentioned above through subjecting the yield surface to various transformations, such as proportional expansion, translation, rotation and distortion [17]. Standard models involving combined isotropic and kinematic hardening effects are limited to modeling only proportional expansion and translation which might not be sufficient in accurate modeling of multistage metal forming processes involving strong load path changes. Baltov and Sawczuk [18] represent one of the early works that takes into account the shape change of the yield surface during deformation known as distortional hardening. The frameworks of Baltov and Sawczuk [18], Levkovitch and Svendsen [19], Clausmeyer et al. [20], Pietryga et al. [21], Barthel et al. [22] and Barlat et al. [23] account for the texture evolution due to the interaction of dislocation structures using evolving structural tensors besides initial anisotropy and combined isotropic and kinematic hardening. The models of the Teodosiu group, e.g., [24–27] with modifications proposed by Wang et al. [28] constitute other phenomenological approaches for modeling distortional hardening effects which, as opposed to the formerly listed models, involve strong coupling between the kinematic hardening and distortional hardening formulation. This makes basic model interpretation and parameter identification relatively tough. Uenishi and Teodosiu [29] presented an extension of the previous model of the Teodosiu group to include the rate effects to describe the behavior of IF steel in crash analysis correctly. Finally, the works of Feigenbaum and Dafalias [30,31] and Plesek et al. [32] represent thermodynamically consistent distortional hardening models where the yield surface curvature at the vicinity of the loading and flattening at the opposing region can be modeled.

In the present work, following in the footsteps of the approaches proposed by Levkovitch and Svendsen [19] and Barthel et al. [22], we present a framework for rate-dependent plasticity accounting for inherent and induced plastic anisotropy as well as Bauschinger effect aiming at modeling the interstitial free (IF) steel behavior, specifically for DC06. For this purpose we devise an anisotropic yield function of Hill-48 type (cf. [33]). The fourth-order structural tensor is not taken as an invariant. However, it is assumed to evolve, where its evolution is formulated in two parts such as dynamic and latent parts in accordance with the dynamics of dislocation structures. In this way, the strength evolution associated not only with the currently active slip systems but also with the latent slip systems is taken into account, the latter of which is also known as cross hardening. The geometrical implications of the current formulation are determined by the quadratic structure of the yield locus which is preserved even during its evolution. Within this limit, e.g., rotation of the axes and the change of the aspect ratio of the ellipse representing the yield locus at the plane stress space is captured. The uniform extension of the yield locus and its shift are taken into account using a combined nonlinear isotropic and Armstrong–Frederick type kinematic hardening. This way the early re-yielding at the load reversals, i.e., the Bauschinger effect, and successive transient hardening is incorporated in the model as an eminent requirement for DC06. The IF steel DC06 is reported as the most strain rate sensitive IF steel among those being applied in automotive industries [34]. A strain rate dependent model is formulated in the current work in terms of a Johnson–Cook type formulation. The experimental curves for DC06 at different strain rates reported by van Riel [35] as well as the experimental data from [20,36,37] are used to identify the corresponding material parameters. The Teodosiu and Hu model [24] and the Levkovich model [19] both are capable of predicting the cross hardening behavior, however the strain rate effect is not included in the Levkovich model. The Teodosiu and Hu model on the other hand also considers strain rate effects however at a cost of totally 7 parameters devoted to the cross hardening (cf. [35]). In the current model, as compared to Teodosiu and Hu only 4 parameters are used for this purpose. Finally, possible change of the Young's modulus due to plastic strain or anisotropy is not accounted for in this work.

The finite strain formulation is based on a Green–Naghdi–McInnis-type hypo-elastic plastic formulation. Accordingly, additivity of the rate of deformation tensor into elastic and plastic parts is assumed. By expressing the yield function in terms of the rotated Cauchy (true) stresses the material frame indifference is naturally satisfied. The developed framework is implemented as a VUMAT user defined material subroutine for ABAQUS/Explicit. First, sensitivity analyses are performed using single finite element tests. Hereby, plane strain tension followed by simple shear and cyclic simple shear with varying amplitudes are realized in a strain controlled fashion. These analyses show that the proposed model appropriately reflects the targeted features such as cross hardening at orthogonal loading path changes, early re-yielding and transient hardening with reversed cyclic loading paths and positive rate dependence of the plastic hardening. Finally, following the corresponding material characterization studies the model is used in the simulation of a channel forming process of DC06 steel sheet. Comparisons of the simulation results with the experimental observations show very good agreement in both the tool response, i.e., the punch force demand history curve, such as the extent of the spring-back which is conclusive on the final product geometry.

The key features in the current approach can be listed as follows:

- Inclusion of rate dependence using a Johnson–Cook type formulation with parameter identification.
- Consistent implementation in ABAQUS/Explicit as VUMAT.
- Sensitivity analysis of the material model with respect to different hardening effects.
- Application of the model to an actual metal forming experimental process.

1.1. A word on notation

In the rest of the paper, the following notations will be used. Consistently assuming $\mathbf{a}$, $\mathbf{b}$, and $\mathbf{c}$ as three second-order tensors, together with the Einstein's summation convention on repeated indices, $\mathbf{c}=\mathbf{a}\cdot\mathbf{b}$ represents the single contraction product with $c_{ik}=a_{ij}b_{jk}$. $d=\mathbf{a}:\mathbf{b}=a_{ij}b_{ij}$ represents the double contraction product, where d is a scalar. $\mathbb{E}=\mathbf{a}\otimes\mathbf{b}$, $\mathbb{F}=\mathbf{a}\overline{\otimes}\mathbf{b}$, and $\mathbb{G}=\mathbf{a}\underline{\otimes}\mathbf{b}$ represent the tensor products with $E_{ijkl}=a_{ij}b_{kl}$, $F_{ijkl}=a_{ik}b_{jl}$, and $G_{ijkl}=a_{il}b_{jk}$, where $\mathbb{E}$, $\mathbb{F}$, and $\mathbb{G}$ represent fourth-order tensors. $\mathbf{a}^{\top}$ and $\mathbf{a}^{-1}$ denote the transpose and the inverse of $\mathbf{a}$, respectively. $\partial_{\mathbf{a}}\mathbf{b}$ denotes the partial derivative of $\mathbf{b}$ with respect to $\mathbf{a}$, that is $\partial\mathbf{b}/\partial\mathbf{a}$. $\mathrm{dev}(\mathbf{a})=\mathbf{a}-[1/3]\,\mathrm{tr}(\mathbf{a})\mathbf{1}$ and $\mathrm{tr}(\mathbf{a})=a_{ii}$ stand for the deviatoric part of and trace of $\mathbf{a}$, respectively, $\mathbf{1}$ denoting the identity tensor. $\mathrm{sym}(\mathbf{a})$ and $\mathrm{skw}(\mathbf{a})$ denote symmetric and skew-symmetric portions of $\mathbf{a}$. $\dot{\mathbf{a}}$ gives the material time derivative of $\mathbf{a}$. $\langle x\rangle=[1/2][x+|x|]$ describes the ramp function. The norm of $\mathbf{a}$ is denoted by $|\mathbf{a}|=\sqrt{\mathbf{a}:\mathbf{a}}$. Finally, $\hat{\mathbf{a}}$ is the rotationally neutralized representation of $\mathbf{a}$.

2. Theory

2.1. Material model – small strain formulation

We set the stage by assuming the additivity of the total strain tensor $\mathbf{E}$ into elastic $\mathbf{E}^e$ and plastic $\mathbf{E}^p$ parts viz.

$$\mathbf{E}=\mathbf{E}^e+\mathbf{E}^p. \tag{1}$$

The stress tensor $\mathbf{S}$ is computed from the quadratic elastic strain energy $\Psi^e=[1/2][\mathbf{E}^e:\mathbb{C}:\mathbf{E}^e]$ with $\mathbb{C}^e$ denoting the elastic