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Effect of the kinematic hardening on the plastic anisotropy parameters for metallic sheets

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ABSTRACT

The initial plastic anisotropy parameters are conventionally determined from the Lankford strain ratios defined by $r^{\psi} = \frac{\varepsilon_{22}^{p\psi}}{\varepsilon_{33}^{p\psi}}$ (ψ being the direction of the loading path). They are usually considered as constant parameters that are determined at a given value of the plastic strain far from the early stage of the plastic flow (i.e. equivalent plastic strain of $\varepsilon_{eq}^{p} = 0.2\%$) and typically at an equivalent plastic strain in between 20% and 50% of plastic strain failure (or material ductility). What prompts to question about the relevance of this determination, considering that this ratio does not remain constant, but changes with plastic strain. Accordingly, when the nonlinear evolution of the kinematic hardening is accounted for, the Lankford strain ratios are expected to evolve significantly during the plastic flow.

In this work, a parametric study is performed to investigate the effect of the nonlinear kinematic hardening evolution of the Lankford strain ratios for different values of the kinematic hardening parameters. For the sake of clarity, this nonlinear kinematic hardening is formulated together with nonlinear isotropic hardening in the framework of anisotropic Hill-type (1948) yield criterion. Extension to other quadratic or non-quadratic yield criteria can be made without any difficulty. This parametric study is completed by studying the effect of these parameters on simulations of sheet metal forming by large plastic strains.

Notation

- RFF: Rotating frame formulation,
- TIP: Thermodynamics of the irreversible processes
- First-rank tensor or vector: $\vec{x}$, x_i,
- Second-rank tensor: $\underline{x}$, x_{ij},
- Fourth-rank tensor: $\underline{\underline{x}}$, x_{ijkl},
- Second-rank identity tensor: $\underline{1}$, δ_{ij},
- Fourth-rank symmetric identity tensor: $\underline{\underline{I}}$, $I_{ijkl} = \frac{1}{2}(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk})$,

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- Fourth-rank symmetric deviatoric identity tensor: $\underline{\underline{I}}^{\text{D}}$, $I^{\text{D}}_{ijkl} = \frac{1}{2}(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) - \frac{1}{3}\delta_{ij}\delta_{kl}$,
- Transpose of second-rank tensor: $\underline{x}^{\mathsf{T}}$, $(x_{ij})^{\mathsf{T}} = x_{ji}$,
- Symmetric and skew-symmetric parts of second-rank tensor: $\underline{x} = [\underline{x}]^{\text{S}} + [\underline{x}]^{\text{A}}$

$$[\underline{x}]^{\text{S}} = \frac{1}{2}(\underline{x} + \underline{x}^{\mathsf{T}}),\ [\underline{x}]^{\text{A}} = \frac{1}{2}(\underline{x} - \underline{x}^{\mathsf{T}}),$$

- Hydrostatic part of second-rank tensor: $[\underline{x}]^{\text{H}} = \frac{1}{3}tr(\underline{x})\underline{1}$,
- Deviatoric part of second-rank tensor: $[\underline{x}]^{\text{D}} = \underline{x} - [\underline{x}]^{\text{H}}$,
- Inverse of second-rank tensor: $\underline{x}^{-1}, x^{-1}_{ij}$,
- Inverse of fourth-rank tensor: $\underline{\underline{x}}^{-1}$, x^{-1}_{ijkl},
- Time derivative of second-rank tensor: $\underline{\dot{x}}$, $\dot{x}_{ij}$,
- Simple contraction of two second-rank tensors: $z_{ij} = x_{ik}y_{kj}$,
- Double contraction of two second-rank tensors: $z = \underline{x} : \underline{y} = x_{ij}y_{ji}$,
- Tensorial product of two second-rank tensors: $\underline{\underline{z}} = \underline{x} \otimes \underline{y}$, $z_{ijkl} = x_{ij}y_{kl}$,
- The trace of the second-rank tensor (1st invariant): $x_I = tr(\underline{x}) = x_{kk}$,
- Second invariant of the second-rank tensor: $x_{II} = [tr^2(\underline{x}) - tr(\underline{x}^2)]/2$,
- Determinant of the second-rank tensor (3rd invariant): $det(\underline{x})$,
- Rotated second-rank tensor (with rigid body rotation $\underline{Q}$): $\underline{\bar{x}} = \underline{Q}^{\mathsf{T}}.\underline{x}.\underline{Q}$, $\bar{x}_{ij} = Q_{ki}Q_{lj}x_{kl}$,
- Rotated fourth-rank tensor between isocline and current configurations: $\underline{\underline{\bar{x}}} = (\underline{Q}^{\mathsf{T}} \otimes \underline{Q}) : \underline{\underline{x}} : (\underline{Q} \otimes \underline{Q}^{\mathsf{T}})$, or $\bar{x}_{ijkl} = Q_{ri}Q_{sj}Q_{pk}Q_{ql}x_{ijkl}$.

1. Introduction

Lightweight structural components, needed for many industrial sectors as automotive and aerospace industries, require advanced High Strength Materials (AHSM) such as steels and aluminum alloys. However, because of their low ductility at room temperature, the forming of such types of materials by deep drawing presents several difficulties. Among these difficulties, we find springback, which appears at the end of the deep drawing operation, when the stamping tools are removed. Considerable efforts have been made to predict numerically, with the best accuracy, the springback in sheet metal forming. For a better numerical prediction of the springback, several factors have been studied. Among them, the most important one is the development of constitutive equations to predict the plastic flow under various loading paths as can be found in [1–11]. The mechanical responses of the high-strength materials under complex loading paths as reverse loading–unloading–reloading must be considered for accurate springback simulations involving accurate modeling of the plastic flow and the related various types of work hardening as well as initial and induced anisotropies. In fact, the metal sheets subjected to deep drawing locally exhibit complex loading paths due mainly to bending–unbending. Therefore, the behavior of the material under loading–unloading–reverse loading must be accurately predicted, in addition to the material behavior under usual monotonic simple (1D) loading paths. Because these strain properties cannot be captured by traditional isotropic hardening models, the current tendency is to consider kinematic hardening models. A better description of the stress–strain responses under reverse loading was then proposed by Armstrong and Frederick [12], introducing a non-linear description of the kinematic hardening with the addition of a dynamic recovery terms. This model has been improved further by Chaboche [13] to describe the ratcheting effects during cyclic loading. Teodosiu et al. [14,15] used a kinematic hardening based on a tensor description of dislocation structures growing under the change of loading paths or change of strain path to better reflect the microscopic changes that occur during plastic flow.

Various kinematic hardening models have been implemented to be used in the FEM simulations of sheet metal forming in order to predict as accurately as possible the formability and springback phenomena [3,4,7–11,16–22]. Other approaches have been developed based on classical nonlinear kinematic hardening combined with the distortion of the subsequent yield surfaces [23–30]. More recently, without using the concept of kinematic hardening, a uniform yield surface based on an anisotropic hardening (HAH) was proposed by Barlat et al. [1,2].

Moreover, considering kinematic hardening in the context of anisotropic plastic flow brings out the issue of identification of the anisotropy parameters. Indeed, the latter are conventionally determined using either the Lankford (strain) and/or stress ratios [17,20,31–41]. When making this identification, it is usual to assume that these coefficients are constant during plastic flow. This assumption is valid for models taking into account isotropic hardening. However, when accounting for kinematic hardening, this assumption is no longer valid, as it has been shown in the work by Wu et al. [21].

In this paper, the sensitivity of Lankford strain ratios evolution according to kinematic hardening parameters and its impact on the simulation of thin sheets forming processes is parametrically studied. In the second section, the theoretical framework for the formulation, under large plastic strains, of the anisotropic elastic–plastic constitutive equations accounting for nonlinear mixed (isotropic and kinematic) hardening is presented. In this context, the anisotropy of the plastic flow and that of the yield function are unified by the same anisotropy parameters. In the third section an exhaustive sensitivity analysis of the evolution of Lankford ratios with respect to the kinematic hardening parameters is performed through a parametric study.