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An evolutionary anisotropic model for sheet metals based on non-associated flow rule approach

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ABSTRACT

We present a phenomenological approach to describe the evolution of anisotropy during plastic deformation. In the presented model, anisotropy evolution is described in terms of both distortional hardening and variation of Lankford coefficients. A non-associated flow rule (non-AFR) based Yld2000-2d anisotropic yield model is employed in which separate yield function and plastic potential are considered which attributes excellent accuracy and flexibility to the model. However, as is the case for the majority of phenomenological anisotropic models, the non-AFR Yld2000-2d model preserves the initial anisotropy during the entire plastic deformation. To include evolutionary characteristics in the model, the shape of plastic potential and yield function should be sensitive to plastic deformation. Therefore, we use polynomial functions to describe the pattern present in the evolution of plastic potential and yield functions. The proposed model was evaluated based on experimental results of interstitial free DC06 deep drawing steel. Despite its simplicity, the proposed evolutionary non-AFR Yld2000-2d model shows excellent accuracy in predicting the evolution of Lankford coefficients and yield stresses during plastic deformation.

1. Introduction

Aggregates of single crystals constitute the crystallographic structure of most metals. For a single crystal, considerable anisotropy of mechanical properties, such as different yield stresses at different orientations, is observed. The mechanical anisotropy at crystal level turns into isotropy at macro-scale level in a polycrystalline aggregate with sufficient random crystal orientation distributions [1]. In other words, the average behavior of all single crystals represents the total material behavior. Thus an isotropic yield function seems to be a sufficient assumption for the description of macroscopic behavior in finite element simulations. However, sheet metals undergo severe plastic deformations during manufacturing processes as cold rolling. This introduces a preferential orientation to the grains. Therefore isotropy is no longer the appropriate assumption to represent the mechanical behavior of a rolled sheet metal. Moreover, the anisotropic behavior has been known to have a great influence on the shape of the specimen after the deformation. Earing at the rim of a deep drawn part is a typical example of distinct anisotropic behavior. According to Yoon et al. [2,3], there is a straightforward relation between on the one hand profile and number of peaks of the Lankford coefficients distribution between 0° and 90° orientations and on the other hand number and profile of ears in a deep drawn cup. Furthermore, they described the connection between directional yield stress distribution and the earing profile. This indicates why an accurate prediction of directional Lankford coefficients and yield stresses by an appropriate anisotropic constitutive model can be essential.

Focusing on constitutive models in general and more specifically on the yield function, there are two major approaches to describe this behavior for polycrystalline materials. The first approach is crystal plasticity and the second one is the phenomenological approach. In the first approach, the behavior of one grain or a distribution of grains around a specific orientation is used to describe the polycrystalline behavior [4–6]. In the phenomenological approach, on the other hand, the average behavior of all grains determines the global material behavior. According to Barlat et al. [7], using a phenomenological yield function has advantages over its microstructure-based counterpart mainly due to its easier implementation in FEM leading to fast computation, description of global anisotropy and easy adaptation for different materials.

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Nomenclature

α_{1-8}	parameters of Yld2000-2d model	$\boldsymbol{m}$	first order gradient of the yield function
b	parameter of Voce isotropic hardening law	υ	Poisson's ratio
c	weight coefficient in combined Swift-Voce hardening	n	parameter of Swift isotropic hardening law
E	Young's modulus	$\boldsymbol{n}$	first order gradient of the plastic potential
$\bar{\varepsilon}^p$	equivalent plastic strain	Q	parameter of Voce isotropic hardening law
ε_{11}^p	longitudinal plastic strain	R	parameter of Voce isotropic hardening law
$\boldsymbol{\varepsilon}^p$	plastic strain tensor	r_θ	r-value at θ degrees orientation w.r.t. rolling direction
$\bar{\varepsilon}^p$	parameter of Swift isotropic hardening law	r_b	r-value coefficient at balanced biaxial state
f	yield function (associated flow rule)	$\boldsymbol{\sigma}$	Cauchy stress tensor
f_y	yield function (non-associated flow rule)	σ_0	true stress in rolling direction
f_p	plastic potential (non-associated flow rule)	σ_θ	initial yield stress at θ degree orientation w.r.t. rolling direction
F	yield criterion	σ_b	initial yield stress at balanced biaxial state
F_{11}	uniaxial tensile load	σ^{iso}	isotropic hardening function
k	parameter of Swift isotropic hardening law	θ	loading direction w.r.t. rolling direction
λ	plastic multiplier factor		
m	parameter of Yld2000-2d model (6 for BCC and 8 for FCC metals)		

Many phenomenological yield functions have been successfully implemented in finite element codes to simulate the isotropic or anisotropic behavior of a material. In general they make use of different combinations of yield stresses and Lankford coefficients (r-values) to represent a multi-dimensional surface determining the transition between elastic and plastic deformation. The foundation of most anisotropic yield functions is based on the Associated Flow Rule (AFR) hypothesis which states that the yield function is also the potential for plastic strain rate. In other words, AFR reflects the normality rule based on which the gradient of a continuously differentiable yield function determines the direction of plastic strain rate. Accordingly, under the assumption of AFR and in the light of material orthotropy, starting from Hill's quadratic anisotropy model [8], various phenomenological yield functions have been proposed to describe the initial anisotropy of metallic sheets. Examples are Karafillis and Boyce [9], Barlat et al. [10–13], Cazacu and Barlat [14,15], Bron and Besson [16], Banabic et al. [17], Vegter and van den Boogaard [18], Cazacu et al. [19,20] and Hu [21]. In order to accurately describe both yielding and plastic flow behavior of sheet metals, the coefficients of the above anisotropic yield functions commonly need to be optimized explicitly or iteratively from experimentally determined tensile, shear or bi-axial yield stresses and r-value coefficients. Except for the model of Hu [21], none of the stated models are in their original formulation able to take distortional anisotropy into account.

During the last decade, more attention has been paid on the development and implementation of non-AFR for metal plasticity. The non-AFR removes the artificial constraint of equality of plastic potential and yield function enforced by the AFR assumption. Consequently, two separate functions for yield and plastic potential are adopted. In other words, the yield function and plastic potential respectively describe the elastic limit and plastic strain rate direction independently. Therefore, a larger number of experimental data can be used for calibration of each yield function and plastic potential parameter resulting in a better agreement between simulation and experimental data, e.g. better prediction of yield stress and r-value at additional orientations.

A limited number of studies have been published on using non-AFR for metal forming applications. For instance, Stoughton [22] proposed a non-AFR model based on Hill 1948 quadratic formulation that accurately predicted both direction dependent r-values and yield stresses in rolling, transverse and diagonal directions. Continuing his previous model, Stoughton with Yoon [23] developed a pressure sensitive non-AFR model that predicted the strength differential effect observed in tension and compression tests. Cvitanic et al. [24] developed a non-AFR model based on both Hill 1948 quadratic and Karafillis and Boyce non-quadratic yield functions combined with isotropic hardening, which showed an improved prediction of cup heights for deep drawn cups. Stoughton and Yoon [25] proposed a non-AFR based anisotropic hardening model that resulted in excellent predictions of hardening curves for rolling, transverse and diagonal directions and for the balanced biaxial stress state. Improvements in prediction of cup height and springback of a U-bend specimen using non-AFR with mixed isotropic-kinematic hardening have been reported by Taherizadeh et al. [26]. Recently, Safaei et al. [27] proposed the combination of a general non-AFR yield model with a recently proposed mixed hardening law which adds the prediction of permanent softening into the capabilities of the classical Chaboche [28] hardening model. Moreover, they showed that the same order of accuracy as obtained by the Yld2004-18p model could be achieved by the non-AFR Yld2000-2d model.

Distortional anisotropy associated with texture evolution can be described as the combination of changes in the shapes of both yield and plastic potential surfaces during plastic deformation. The evolution of the yield surface shape, which is commonly referred to as distortional hardening, represents the distortional anisotropy if only AFR is considered. For example, distortional hardening was reported by experimental results of Khan et al. [29]. As discussed earlier, there is a relation between earing profile in a cylindrical deep drawn cup and the distribution of in-plane Lankford coefficients and yield stress ratios. Different studies validated the sensitivity of the cup profile to the shape of yield function and plastic potential [3,27,30]. Moreover, it has been reported that the prediction of localized necking in sheet metals is quite sensitive to the shape of the yield surface [31,32]. Considering all the above, final shape and failure of deep drawing products are not only influenced by the initial, but also by the subsequent shapes of plastic potential and yield surfaces during deformation.

Different attempts have been made to model such distortional hardening effect. For instance, Feigenbaum and Dafalias [33] and Pietryga et al. [34] proposed distortional hardening models based on an evolving fourth order tensor. Plesek et al. [35] discussed the convexity of the model proposed by Feigenbaum and Dafalias [33]. Wang et al. [36] proposed a distortional hardening model that captures hardening stagnation after a load reversal as well as cross-hardening after orthogonal loading-path changes. A new