International Journal of Mechanical Sciences 107 (2016) 43–57

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Constitutive modeling of evolving plasticity in high strength steel sheets

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ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form
22 October 2015
Accepted 5 January 2016
Available online 11 January 2016

Keywords:
High strength steel
Evolving plasticity
FEM
Biaxial tensile test
Earing prediction

ABSTRACT

In this paper, biaxial tensile tests with cruciform specimens were conducted to obtain the experimental plastic work contours of DP590, DP780 and DP980 sheets. It was found that for high strength dual phase steel sheets, the outlines of the experimental work contours in the first quadrant evolve evidently with the increase of plastic dissipation. In order to calibrate the evolving isotropic and anisotropic plastic behaviors simultaneously, the Yld2000-2d yield criterion with variable exponent and coefficients (Yld2000-2d-Var) was introduced. In this model, the exponent m and coefficients α_i of the Yld2000-2d was assumed as the function of the equivalent plastic strain. The identification procedures of the introduced parameters were then proposed based on minimizing the difference between the experimental and the model predicted yield points, using Levenberg–Marquardt optimization method. Afterwards, the proposed model was implemented into ABAQUS as user subroutine VUMAT with semi-implicit back-Euler integration algorithm. The numerical simulations of hydro-bulging and cylindrical deep drawing tests were then carried out to verify the validity of the proposed model. The results showed that the proposed model could enhance the predicting accuracy in both tests due to its flexibility.

1. Introduction

The application of the advanced high strength steel alloys (AHSS) has been increasing in the automobile industry for the weight reduction and collision-safe performance. However, AHSS sheets are difficult to form in sheet metal forming processes, as they have relatively complex microstructures which lead to a typical plasticity. Compared with tradition trial-and-error method, Finite Element Method (FEM) is a promising way in designing the process of AHSS, since it can lower the cost remarkably with better precision in forming prediction. Nevertheless, the confidence in the FEM formability analysis strongly relies on the accuracy of the constitutive model which describes the plastic behavior of the materials [1]. This is crucial to the material exhibiting anisotropic behavior, as most cold-rolled sheet metals do.

Anisotropic behavior of the sheet metals has been studied in great depth and consequently a number of anisotropic yield criteria have been proposed. Generally, the anisotropy is introduced by adding a number of anisotropic coefficients to the original isotropic yield function. For instance, Hill's quadratic yield function [2], widely used for its simplicity, is derived from von Mises yield function by introducing six orthotropic parameters. It has been proven that Hill's quadratic yield function is capable in predicting the formability of some ferrous metal alloys [3]. To precisely describe the deformation behavior of the aluminum alloys, Barlat et al. [4–7] proposed a series of anisotropic yield functions based on Hosford isotropic criterion [8]. Similar approach was then performed by Banabic et al. [9–12]. These Hosford derived criteria improve their precision by adding more coefficients to the functions, which would inevitably complicate the yield function and thus lower the computational efficiency in the simulations [12]. For the propose of introducing more coefficients without complicating the form of the yield function, Karafillis and Boyce [13] proposed the idea of isotropic plastic equivalent (IPE), which introducing the anisotropy by linearly transforming the stress tensor. Inspired by Karafillis and Boyce, Barlat et al. [14] then performed two independent linear transformations on the deviatoric stress tensor and formulated the Yld2000-2d yield function. Afterwards, more flexible yield function were proposed by Barlat et al. [15], Cazacu et al. [16], Aretz et al. [17], etc. using the similar approach. It should be noted that these yield criteria are all phenomenological and need to be verified and tested before applying on the AHSS sheets.

Recently, some studies have been carried out on the applicability of present yield criteria for AHSS sheets. Mohr et al. [18] proposed that the Hill quadratic yield criterion combined with

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http://dx.doi.org/10.1016/j.ijmecsci.2016.01.006
0020-7403/

non-associated flow rules could provide good estimates for dual phase and TRIP-assisted steel under multi-axial loading. Padmanabhan et al. [19] used this yield criterion with Swift hardening law to predict the square cup deep-drawing of the dual phase steel tailor-welded blanks. Nevertheless, Andar et al. [20] performed a series of biaxial tensile tests on DP590 and suggested that the Yld2000-2d yield function could describe the yield behavior of the dual phase steel sheets with better precision. Detailed experimental investigations were then carried out by Kuwabara et al. [21] to reveal the yield behavior of DP980 under tension–compression and pure shear states. It indicated that the Yld2000-2d yield function with exponent of 4 could have better agreement with the experimental data. The identical yield function, combined with modified Chaboche hardening model, was adopted by Ahn et al. [22] in simulating the springback of TWIP-assisted steel sheets with enhanced accuracy. It could be concluded that both Hill quadratic and Yld2000-2d yield criteria are commonly applied in the AHSS sheet, while the Yld2000-2d might exhibit some advantages in predicting with higher precision.

Conventionally, the anisotropic coefficients adopted in the yield functions were associated with material properties at the initial yield point. In this paper, however, it would indicate that the plastic behavior of some AHSS sheets evolves obviously during the deformation, thus the constitutive model could lead to an inaccurate result if just using the material properties at one single stage. Recently, the phenomenon of evolving anisotropy was studied mostly for hexagonal-close-packed alloys and aluminum alloys for their complex microscopic deformation mechanism. Plunkett et al. [23,24] observed strong evolving anisotropy during the deformation of the high-purity zirconium and then proposed a modified CPB06ex3 yield criterion with variable anisotropic parameters. The parameters corresponding to an arbitrary equivalent plastic strain are determined by linearly interpolating between the pre-computed parameters associated with several fixed levels of equivalent plastic strain. Based on Plunkett, Ghaffari Tari et al. [25] suggested another CPB06ex3 derived model to calibrate the evolving anisotropy and asymmetry of the AZ31B-O magnesium alloys. In Ghaffari's model, the anisotropy and asymmetry parameters of the CPB06ex3 yield function are replaced with Voce-type functions expressed in terms of plastic strain. Yoon et al. [26] found the similar phenomenon in the AA5042-H2 aluminum alloy and proposed the modified Yld2000-2d and CPB06ex2 yield functions with dynamically updated anisotropy coefficients. Since the anisotropy coefficients of Yoon's yield functions should be computed and updated in each incremental step instantly by solving nonlinear equations, the computational efficiency of these two modified yield functions is unsatisfying. Wang et al. [27] also observed the similar evolving anisotropy in the AA5754-O aluminum alloy, and proposed a modified Yld2000-2d yield criterion which considers the evolving of anisotropy. In Wang's model, the 8 anisotropy coefficients of the Yld2000-2d are expressed as sixth-order polynomial functions of the equivalent plastic strain. With the modified yield model, Wang successfully enhanced the accuracy of predicting earing profile in deep drawing test. For the above studies, they all focused on the changes of the anisotropic coefficients in the yield functions to calibrate the anisotropic part of the evolving plasticity. The change of the exponent in the yield function, however, has not been taken into consideration, which leads to incapability in describing the isotropic part of the evolving plasticity.

The earing behavior of cold-rolled sheet metal was noticed in the early applications of the cylindrical deep drawing process. Detailed analyses have been conducted on the dependency between the earing amplitude and the planar anisotropy. Yoon et al. [28] proposed an analytical approach with arbitrary anisotropic yield function to determine the earing profile in the drawing and redrawing processes. It indicated that the distribution of earing has strong dependency on the *r*-value and yield stress directionalities. Further works conducted by Chung et al. [29] proved that the earing profile could be determined analytically only with the anisotropic properties of yield stress and the *r*-value. With the development of the numerical simulating techniques, the earing prediction could be obtained by finite element simulations. The analyses of the FEM predictions revealed that earing profile has significant dependency on the chosen constitutive model, especially the yield criteria. Therefore, it has been widely accepted that the comparison of FEM predicted earing profile with the experimental one is a convincing way to evaluate the capability of proposed anisotropic yield criteria [12,27,30].

In this paper, the experimental plastic work contours of DP590, DP780 and DP980 sheets were obtained with biaxial tensile tests. Inspired by the evolving trend of the subsequent plastic work contours, the Yld2000-2d yield criterion with variable exponent and coefficients (Yld2000-2d-Var) was proposed to calibrate the anisotropic and isotropic parts of the evolving plasticity simultaneously. The proposed model was then implemented into ABAQUS as user subroutine VUMAT. Afterwards, the finite element analyses of hydro-bulging tests were carried out with different constitutive models (Mises, Hill48, Yld2000-2d and Yld2000-2d-Var). Besides, the deep drawing tests were also carried out and were simulated with different yield criteria. The validity of the proposed model was verified by comparing the experimental and FEM predicted results.

2. Materials and experiments

2.1. Materials

The materials used in this paper were the dual phase steel sheets with tensile strength of 590 MPa, 780 MPa and 980 MPa, which produced by BaoSteel, Inc. The thickness of DP590 sheets was 1.5 mm, while DP780 and DP980 were 1.2 mm. The material properties obtained from uniaxial tensile test are listed in Table 1.

Fig. 1 shows the uniaxial nominal stress–nominal strain curves of the DP590, DP780 and DP980 from different tensile directions. These tests were performed on the Instron tensile test machine. From Fig. 1 it could be observed that the DP780 and DP980 sheets exhibited more anisotropy than that of DP590.

2.2. Testing apparatus and specimen

The biaxial tensile testing system used in this study includes a loading test machine, a control unit and related software. It was improved based on the prototype originally designed by Wu et al. [31]. The loading test machine, shown in Fig. 2, has two pairs of

Table 1
Mechanical properties of the materials.

Materials	Direction from RD (deg)[a]	$\sigma_{0.2}$ (MPa)	σ_b (MPa)	*r*-value[b]
DP590	0	398.4	631.7	0.963
	45	404.5	645.3	0.815
	90	387.6	630.0	1.096
DP780	0	552.5	851	0.582
	45	545.7	833	0.943
	90	578.2	887	0.827
DP980	0	706.7	1023	0.609
	45	685.6	991	0.914
	90	724.9	1048	0.749

[a] RD is the abbreviation of Rolling Direction.
[b] Measured at the uniaxial nominal strain $0 < \varepsilon_N < 0.06$