International Journal of Mechanical Sciences 85 (2014) 142–151

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Calibration of anisotropic yield criterion with conventional tests or biaxial test

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ARTICLE INFO

Article history:
Received 18 December 2013
Received in revised form
6 May 2014
Accepted 19 May 2014
Available online 26 May 2014

Keywords:
Plastic anisotropy
Yield criterion
Biaxial test
Material parameter identification

ABSTRACT

Bron and Besson yield criterion has been used to model the plastic anisotropic behavior of an aluminum alloy series 5000. The parameters of this anisotropic yield model have been identified by two different methods: a classical one, considering several homogeneous conventional experiments and an exploratory one, with only one biaxial test. On one hand, the parameter identification with conventional experiments has been carried out with uniaxial tensile and simple shear tests in different orientations to the rolling direction and with a hydraulic bulge test, all of them considered at three equivalent plastic strain levels. On the other hand, Bron and Besson yield function has also been calibrated with inverse analysis from only a cross biaxial tensile test, since it was shown that the strain distribution in the center of the cruciform specimen is significantly dependent on the yield criterion. The principal strains along a specified path in the gauge area of the cruciform specimen have been analyzed and the gap between experimental and numerical values was minimized. Finally the yield contours obtained with the two methods have been compared and discussed.

1. Introduction

Sheet metal forming represents a class of important processes widely used in the manufacturing industry. Sheet metals usually exhibit a plastic anisotropy due to previous thermo-mechanical processes like rolling and annealing. To optimize the numerical simulation of the forming processes, an accurate description of the plastic behavior is required. Within a phenomenological description of the mechanical behavior of sheet metals, yield functions and especially anisotropic ones are used to represent the initial anisotropy of the material. Many anisotropic yield models were proposed to describe the initial anisotropy and identified from the mechanical properties, such as Hill 1948 [1], Barlat [2] (Yld 2000-2d), Barlat [3] (Yld2004-13p/18p) yield models and Karafillis–Boyce [4]; a thorough review of these models is presented in [5]. The initial anisotropy description, coupled with hardening evolution, can lead to a good representation of the mechanical behavior over a large strain range, e.g. [6]. An alternative consists in taking into account anisotropy evolution, as proposed in [7]. To consider the plastic strain-induced anisotropy, Zang and Lee [8] carried out the eigen decompositions of the linear transformation tensors of Yld2000-2d yield model at different equivalent plastic strains. Such an approach with the variation of anisotropic coefficients is not considered in this study, where plastic anisotropy coefficients are considered constants, over the investigated strain range.

Yield functions can involve a high number of material parameters. The calibration of these parameters requires usually several mechanical tests with different loading paths. To guarantee the relevance of the parameter set, the number of experimental data should not be lower than the number of material parameters considered in the identification process. In the case of the classical analytical approach, the experimental values, such as initial yield stresses and plastic anisotropy coefficients, obtained from mechanical tests are used as discrete input data or sampling points. The yield function makes an interpolation in-between these sampling points. Ideally, if the model is able to represent the mechanical behavior of the material, the interpolation points of the yield function correspond to these sampling points precisely. The relevance of the yield contour is improved when increasing the number of sampling points, demanding an increase of experimental information. However, from an economical point of view, the number of tests should be as small as possible. It has been proposed in [5] that at least the following experimental data

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http://dx.doi.org/10.1016/j.ijmecsci.2014.05.020
0020-7403/

is required: three yield stresses (e.g. σ_0, σ_{45} and σ_{90}) and three anisotropic coefficients (e.g. r_0, r_{45} and r_{90}) obtained from the uniaxial tensile tests in different orientations to the rolling direction (RD); an equi-biaxial yield stress (σ_b) and a biaxial coefficient (r_b) from biaxial tensile test, usually hydraulic bulge test. As mentioned above, most of the previous works proposed identification based on the initial values of these data, measured at the elasto-plastic transition. For the classical Hill 1948 yield criterion [1], three values among the ones indicated above are needed to calibrate three parameters in the case of a plane stress state. For the same stress condition, four values are needed to determine Barlat yield criterion involving four parameters [9]. Aretz [10] identified eight parameters of Barlat yield model (Yld2003) [11] with all the above-mentioned input data. Another method [12] was also proposed to identify this eight parameter yield model; indeed, the bulge test was replaced by two plane strain tensile tests. The major stresses at plastic yielding were taken as the input data. With the two linear transformation tensors introduced by Barlat [2], yield models were developed to be more and more flexible, such flexibility being related to the increase of the number of material parameters. Barlat and co-authors [3] calibrated the yield function Yld2004-18p with all the above-mentioned data and with additional data: the initial yield stresses and anisotropic coefficients from uniaxial tensile tests along 15°, 30°, 60° and 75° to RD. Bron and Besson yield model [13], also based on two linear transformation tensors, was identified similarly with a total of 16 parameters. From 2000, Banabic et al. proposed a series of yield models, which are called BBC yield models. For the 8 parameter yield criterion BBC2005 [14] and 16 parameter BBC2008 [15], Banabic et al. used the same input data as the above mentioned Yld2003 and Yld2004-18p respectively.

However, Hu [16] pointed out that the initial yield stresses were difficult to determine accurately since there exist several definitions of initial yielding. Some works investigated the identification of material parameters considering not only the initial values but also values recorded at higher strains. To predict the earing phenomenon in drawing and ironing process, Barros et al. [17] made a comparison of Cazacu and Barlat yield model [18] identified either from initial yield values or from the ones at an accumulated plastic work of 20 MPa. It is clearly shown that the yield model identified at an accumulated plastic work of 20 MPa gives a better description of the material mechanical behavior than the one identified from the initial values. Wang et al. [19] also proposed a strain-dependent identification method by considering the variation trend of the material values at different plastic strain levels. Another approach without considering initial yield stress values consists in parameter identification over the temporal evolution of experimental data. Zang et al. [6] considered a combination of stress level in uniaxial tension, equi-biaxial tension and simple shear, both monotonic and Bauschinger tests, to identify Bron and Besson yield function. Bron and Besson [13] also proposed a similar identification strategy with the temporal evolution of stress levels in tensile tests, both on straight and U-notched samples. It can be concluded that due to the dispersion on initial yield stresses as well as the evolution of anisotropy with strain, considering only initial yield stresses does not give an accurate description of the mechanical behavior. In this paper, the experimental values were obtained at several plastic strain levels.

Recently, some works have been focused on parameter identification of yield functions from the biaxial tensile test. Green et al. [20] have performed cross biaxial test with seven different proportional strain paths, in order to identify the parameters of several yield functions, some of them could not be identified by uniaxial tensile test but only with biaxial test. The authors adjusted the parameters with an iterative procedure to optimize the predicted strength level of two arms of the cruciform sample. Teaca et al. [21] proposed to identify Ferron, Makkouk and Morreale (FMM) yield function parameters [22] by combining results of uniaxial tensile tests and cross biaxial test. However, only two parameters of the yield model were calibrated from the strain distribution in the central part of the cruciform specimen. The field measurement of the strain level was also used by Prates et al. [23] to identify Hill 1948 coefficients. Up to now and to the authors' knowledge, there is no published work that concerns the parameter identification of a complex yield model with only one cross biaxial tensile test.

In the present article, Bron and Besson yield model is used to investigate the plastic anisotropy of AA5086 sheets. This yield model is flexible enough since the anisotropy is represented by 12 parameters, in the form of two linear fourth order transformation tensors; i.e. 4 isotropic parameters and 8 anisotropic parameters in plane stress condition. In order to identify these parameters, with two different methods, the mechanical behavior of AA5086 sheets of 2 mm thickness is investigated with homogeneous tests, like tension and simple shear, both at different orientations to RD, and hydraulic bulging, and also with cross biaxial test; all these results are original ones. The first identification method is based on an analytical description of the homogeneous conventional experiments. The experimental values at different equivalent plastic strain levels are obtained from these tests as the input values. Hill 1948 yield function was also calibrated with these conventional results. It is shown that the numerical prediction of the strain distribution at the cruciform specimen center is significantly modified by the yield criterion. The second method relies on the cross biaxial tensile test and all parameters of Bron and Besson yield function are identified with a cruciform specimen since it is shown that the strain distribution in the central area of the specimen depends significantly on the yield criterion. Comparison between experimental and numerical results of principal strains along a specified path in the gage area of the cruciform specimen is performed. It is shown that the cross biaxial test involves a large range of strain paths, though the maximum strain is limited. Finally, the yield models identified by the two identification methods are compared.

2. Material model

Assuming orthotropic symmetry, $(\vec{1}, \vec{2}, \vec{3})$ are respectively the rolling direction (RD), the transverse direction (TD) and the normal direction (ND). In the frame of a uniaxial tensile test, $(\vec{x}, \vec{y}, \vec{z})$ are respectively the tensile direction, the transverse direction in the sheet plane and the normal direction.

2.1. Hill 1948 yield function

Hill 1948 orthotropic yield function is written in the following form [1]:

$$\psi_H = F(\sigma_{22}-\sigma_{33})^2 + G(\sigma_{33}-\sigma_{11})^2 + H(\sigma_{11}-\sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{13}^2 + 2N\sigma_{12}^2 \tag{1}$$

where ψ_H denotes the yield function. Plastic yielding occurs when $\psi_H = \overline{\sigma}^2 = Y_0^2$ where $\overline{\sigma}$ is the equivalent stress and Y_0 a reference yield stress of the material. F, G, H, L, M and N are material parameters. When the condition $G+H=1$ is imposed, Y_0 is the uniaxial yield stress along the rolling direction. Then, with plane stress condition ($\sigma_{33}=\sigma_{13}=\sigma_{23}=0$), three independent anisotropic parameters F, G and N have to be identified.