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Influence of the characteristics of the experimental data set used to identify anisotropy parameters

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ABSTRACT

This work presents an investigation into the effect of the number and type of experimental input data used in parameter identification of Hill'48, Barlat'91 (Yld91) and Cazacu and Barlat'2001 (CB2001) yield criteria on the accuracy of the finite element simulation results. Different sets of experimental data are used to identify the anisotropy parameters of two metal sheets, exhibiting different anisotropic behaviour and hardening characteristics: a mild steel (DC06) and an aluminium alloy (AA6016-T4). Although it has been shown that the CB2001 yield criterion can lead to an accurate description of anisotropic behaviour of metallic sheets, its calibration requires a large set of experimental input data. A calibration procedure is proposed for CB2001 based on a reduced set of experimental data, i.e. where the results are limited to three uniaxial tensile tests, combined with artificial data obtained using the Barlat'91 yield criterion. Evaluation of the predictive capacity of the studied yield criteria, calibrated using different sets of experimental data, is made by comparing finite element simulation results with experimental results for the deep drawing of a cross-shaped part. A satisfying agreement is observed between experimental and numerical thickness distributions, with a negligible effect of the number and type of experimental data for the Hill'48 and Yld91 yield criteria. On the contrary, CB2001 calibration is quite sensitive to the experimental data available, particularly biaxial values. Nevertheless, CB2001 calibration based on the combination of effective and artificial experimental data achieves satisfying results, which in the worst case are similar to the ones obtained with the Yld91.

1. Introduction

The automotive and aeronautical industries are continuously clamouring for new or improved materials for developing better-quality structural parts. The resulting materials are commonly characterised by complex behaviour. This demand must be accompanied by the development of more reliable constitutive models to meet accurate finite element (FE) simulation results. Nowadays, FE simulation is an essential tool for testing and developing new parts, particularly in industrial environments, owing to the associated significant reduction in expensive experimental costs. However, FE predictions are highly dependent on accurately describing the material's mechanical behaviour, i.e. the selected constitutive model as well as the input data used for its calibration. Nonetheless, accurately describing the material's behaviour also depends on the number

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and type of available data measurements from mechanical tests. In fact, over recent decades several advanced constitutive models have been proposed and they require a large number of varied experimental data for their calibration. These phenomenological models are typically based on the use of plastic potentials and associated flow rules and have been successfully applied in FE analysis of deep drawing processes. Hence, they are successfully and intensively implemented in both academic and commercial FE packages. The yield criteria of Tresca and von Mises are the most widely used for describing isotropic metallic materials. The latter criterion was the basis for the development of the first orthotropic yield criterion, proposed in 1948 by Hill (Hill48) [1]. Nowadays, von Mises and Hill48 are the most implemented of all yield criteria in FE codes. Later, Hershey [2] and Hosford [3] introduced a generalised isotropic yield function with a variable exponent that takes into account the material's crystallographic structure [4]. This yield function was generalised for anisotropic metals by Barlat et al. [5]. Karafillis and Boyce [6] introduced the anisotropy parameters using the concept a fourth-order tensor in a linear transformation of the Cauchy stress tensor. The linear transformation approach, applied to the deviatoric stress tensor, is attractive since it assures the yield function's convexity and is a convenient means of introducing a large number of anisotropy parameters in the new yield criteria formulation, increasing their flexibility [7]. Based on this approach, Barlat et al. [8] proposed an extension of Yld91, the so-called Yld96, which involves seven anisotropy coefficients under a plane stress state. Later, a plane stress yield function using two linear transformations of the deviatoric stress tensor, referred to as Yld2000-2d, was proposed. This yield criterion involves eight independent anisotropy coefficients [9]. Thereafter, Barlat et al. [10] developed the Yld2004-18p yield criterion, also based on two linear transformations, which was established for a pressure independent material under general stress conditions. For plane stress conditions, the eighteen independent anisotropy parameters involved in this yield function are reduced to fourteen [11]. Furthermore, it has been shown that Yld89 [12] and Yld91 yield criteria [5] are particular cases of the more recently proposed criteria, i.e. Yld2000-2d and Yld2004-18p, respectively [7].

Aretz and Barlat [13] suggested a new yield function for orthotropic metal sheets, considered to be complementary to the Yld2004-18p and so-called Yld2011-18p. The later was extended to the so-called Yld2011-27p yield criterion, which involves a total of twenty-seven anisotropy parameters. This shows that the concept of using multiple linear transformations of the deviatoric stress tensor enables the construction of more flexible yield criteria, associated with a larger number of anisotropy coefficients. However, using multiple linear transformations, analytical computation of the yield function gradient is quite complex and its numerical implementation is prone to errors [13].

Aware of the limitations of quadratic yield criteria, Hill proposed a general homogeneous polynomial formulation as a yield function for plane stress states [14]. Gotoh was the first to explore the use of a fourth-order polynomial as a plane stress yield function [15]. Gotoh suggested the use of eight directional uniaxial tensile properties and the balanced biaxial stress to identify the nine anisotropy parameters of the yield criterion. It was the first yield function that could simultaneously describe both directional yield stresses and r-values. Nevertheless, the shortcoming of using a polynomial function for yield criterion formulation is the lack of evidence of convexity conditions. Additionally, any anisotropic yield function should be reduced to an isotropic function by imposing constraints on its anisotropy parameters. In this context, Cazacu and Barlat proposed an extension of Drucker's isotropic criterion [16] to anisotropy, based on the formulation of a sixth-order polynomial function. The CB2001 yield criterion involves eighteen anisotropy parameters under a general stress state and eleven coefficients for plane stress conditions, enabling the description of a wide range of anisotropic material properties [17,18].

Concurrently, Banabic et al. [19] developed a plane stress yield criterion, referred to as BBC2000, which was derived from the criterion proposed by Barlat and Lian in 1989 (Yld89) [12]. The Yld89 yield function uses eight anisotropy parameters to describe anisotropic behaviour, along with an exponent coefficient related to the material crystallographic structure [4]. Banabic et al. improved the BBC2000 criterion by rearranging the anisotropy parameters, offering more possibilities for adjusting these parameters to the experimental data. This yield criterion, referred to as BBC2005, encompasses eight independent anisotropy coefficients [20,21]. Barlat analysed Yld2000-2d, BBC2005 and the yield function proposed by Aretz in 2004 [22,23] and pointed out that for plane stress conditions, these yield criteria are similar [7]. Comsa and Banabic formulated BBC2008 as a finite series of anisotropy parameters that can be expanded or reduced from eight to twenty-four parameters, depending on the available number of experimental data measurements [24]. Vrh et al. demonstrated the ability of the BBC2008 yield criterion to predict the earing profiles in a cylindrical deep drawing cup, for two anisotropic aluminium alloys [25].

Based on this brief literature review, it can be noted that several sophisticated yield criteria are being continuously proposed, trying to enhance the description of the anisotropic plastic behaviour of metal sheets. Moreover, it has been shown that the ability of a yield criterion to describe the material's anisotropic behaviour depends on its flexibility, which in turn is related to the number of anisotropic parameters. As a consequence, the necessary number and type of experimental tests for the calibration of flexible yield criteria increases [13,25,26]. However, the cost associated with a large number of different types of experimental tests along with the mathematical complexity of the advanced yield criteria are the major shortcomings contributing to a limited use in an industrial environment. In order to enhance the application of advanced yield criteria in the sheet metal forming industry, some attempts have been made to narrow the gap between yield function calibration costs and its efficiency for describing anisotropic material behaviour. In this sense, it is of paramount importance to investigate less expensive parameter identification approaches, with the aim of reducing the required sets of experimental input data while maintaining reasonable accuracy. Therefore, Malo et al. [27] proposed a strategy to determine the anisotropy parameters of the Hill48 and Yld89 yield criteria using stress data obtained from tensile and bending tests. However, no validation tests were performed to assess the efficiency of the identification strategy. Wu et al. [28] investigated the