Computational Materials Science 47 (2009) 12–22

Contents lists available at ScienceDirect

Computational Materials Science

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

The equivalent plastic strain-dependent Yld2000-2d yield function and the experimental verification

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ARTICLE INFO

Article history:
Received 11 March 2009
Received in revised form 5 May 2009
Accepted 10 June 2009
Available online 10 July 2009

PACS:
02.70.Dh
07.05.Fb
07.05.Kf
07.05.Tp
62.20.fq
73.43.Fj

Keywords:
Material anisotropy
Yield function
Biaxial tensile test
Finite element method

ABSTRACT

An equivalent plastic strain-dependent anisotropic material model was developed for 5754O aluminum alloy sheet. In the developed model, the anisotropy coefficients for Barlat's Yld2000-2d anisotropic yield function were established as a function of the equivalent plastic strain. The developed anisotropic material model was implemented into the commercial FEM code ABAQUS as a user material subroutine (UMAT) for simulations. In order to evaluate the accuracy of the developed material model, biaxial tensile tests were carried out using cruciform specimens and a biaxial loading testing machine. The results show that the developed material model predicts the experimental results better than the other three material models (Yld2000-2d, Mises and Hill48 yield functions). It is also found that the developed material model describes the uniaxial tensile test curves better than Yld2000-2d yield function. The deep drawing test for 5754O aluminum alloy sheet was carried out and was simulated with different material models. The comparison between the experimental and simulation results indicates that the developed material model predicts the earing profile better than other material models. It is concluded that the equivalent plastic strain-dependence of the material coefficients should be considered for the accurate prediction of the anisotropic deformation behavior of materials.

1. Introduction

In sheet metal forming processes, high prediction precision of both the geometry and the mechanical properties of the final product is required. For this purpose, the development of plasticity theory has been pursued for many years. Compared with the traditional trial-and-error method, FEM is a reasonable choice for investigating the material behavior and optimizing manufacturing processes to cut down the cost. Confidence in the FE analysis of formability depends on the accuracy of the constitutive model describing the behavior of the material [1]. This is especially important when the material exhibits anisotropic characteristics, as most cold rolled sheet metals do [2]. Anisotropic behavior of materials is one of the hottest topics in the field of metal forming and has been studied in great detail [3–6]. In order to describe the anisotropic behavior of materials, a number of anisotropic yield functions have been proposed by Hill [7], Barlat and Lian [8], Barlat et al. [9–13], Karafillis and Boyce [14], Monchiet et al. [15], etc.

Usually, the material coefficients of the yield functions are calculated using the material properties at the initial yield point, such as σ_0 and σ_{90} (the initial yield stresses in the rolling and the transverse directions). However, materials may exhibit different anisotropic behavior during deformation (with the increase of the plastic work). Now take 5754O aluminum alloy sheet which will be used in this study for an example. The uniaxial tensile stress–plastic work (per unit volume) curves of 5754O aluminum alloy sheet along the rolling and transverse directions are shown in Fig. 1. From the stress–plastic work curves, it is found that σ_{90} is greater than σ_0 at the initial yield point, i.e., $\sigma_{90}/\sigma_0 > 1$. However, some special phenomena can be found: the stress–plastic work curve in the transverse direction becomes lower gradually than that in the rolling direction with the increase of plastic work, i.e., $\sigma_{90}/\sigma_0 < 1$. The similar results can also be found from the comparisons between other curves (the stress–plastic work curves along the rolling and 45° directions, etc.). The ratios of the stresses (σ_{90}/σ_0 and σ_{45}/σ_0, etc.) will be used for calculating the anisotropic coefficients of the yield functions. Therefore, the measured material properties at the initial yield point for calculating the material coefficients of the yield functions cannot completely reflect the true material behavior during the deformation process. Yoon and

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doi:10.1016/j.commatsci.2009.06.008

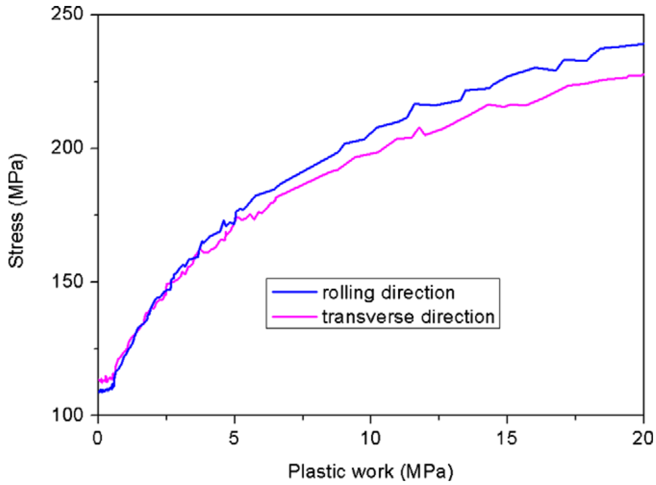

Fig. 1. The stress–plastic work curves in the rolling and the transverse direction.

Barlat [16] recommended that the material properties at fracture point or away from the initial yield point should be taken by utilizing the work equivalent theorem for better predicting both hardening and earing. Certainly there are some points where the material properties can reflect the material behavior better than the other points. However, it is difficult to find one point where the material properties can completely reflect the anisotropic behavior of the materials, especially for the materials which have the special phenomena mentioned above. In other words, the changes of material properties during deformation should be considered to better describe the anisotropic behavior of materials. As to the author's knowledge, there are few phenomenological material models, which consider the changes of anisotropy during deformations.

Therefore, it is necessary to develop a material model that considers the changes of anisotropy during the deformation. In addition, rigorous experimental verification is crucial for ensuring that the developed material model adequately describes the anisotropic behaviors of the materials. Biaxial test is required to quantify and clarify the yield criteria and constitutive equations of a particular material [17]. The hydrostatic bulging of a circular blank leads to large biaxial strains, but it is restricted to only one particular deformation mode. The determination of the complete initial yield surface of a sheet metal using the bulge test is obviously impossible. Some researchers [18–20] have studied thin tubular specimens under multiaxial loadings. However, the test data from such experiments cannot be directly applied to rolled sheets [21]. Biaxial tensile test with different types of cruciform specimens has been used to realize various stress states of biaxial tension by Kuwabara et al. [17,22–24] and Green et al. [25].

In the present work, an anisotropic material model considering the changes of anisotropy was developed by improving Barlat's Yld2000-2d yield function. In order to evaluate the accuracy of this material model, biaxial tensile tests of 5754O aluminum alloy sheet with cruciform specimens were carried out under proportional loading conditions. The developed material model was implemented into implicit commercial codes as a user subroutine UMAT. The finite element analyses of the biaxial tensile tests were carried out with the developed material model and three other material models (Mises, Hill48 and Yld2000-2d yield functions). The deep drawing test was carried out and was simulated with different yield functions. The validity of the developed model is confirmed by comparing the simulated and experimental results.

2. Anisotropic material model

2.1. Mises and Hill48 yield functions

Mises and Hill48 yield functions are already included in ABAQUS commercial codes. Hill48 yield function under a plane stress condition is given by

$$(G+H)\sigma_x^2 - 2H\sigma_x\sigma_y + (F+H)\sigma_y^2 + 2N\sigma_{xy}^2 = \bar{\sigma} \tag{1}$$

where F, G, H and N are material coefficients. When $N = 3G = 3H = 3F = \frac{3}{2}$, Hill48 yield function reduces to Mises yield function.

2.2. Yld2000-2d yield function

In order to alleviate the drawbacks of Yld96 yield function [11], such as the lack of proof of convexity and the difficulty in obtaining the derivatives analytically, Yld2000-2d yield function was proposed by Barlat et al. [12]. Compared to the yield functions previously proposed by Barlat and Lian [8] and Barlat et al. [9,10], Yld2000-2d yield function has eight anisotropy coefficients so that it can accommodate eight mechanical measurements such as σ_0, σ_{45}, σ_{90}, r_0, r_{45}, r_{90} which are simple tension yield stresses and r values along the rolling direction, 45° and the transverse directions, as well as the yield stress σ_b and r_b under the balanced biaxial tension condition, respectively. The orthotropic yield function is reasonably suitable to describe the anisotropy of rolled sheets, especially of aluminum alloy sheets [26–29].

Yld2000-2d yield function is given by

$$\phi = \phi' + \phi'' = 2\bar{\sigma}^m \tag{2}$$

where exponent m is a material coefficient and

$$\begin{cases} \phi' = |X_1' - X_2'|^m \\ \phi'' = |2X_2'' + X_1''|^m + |2X_1'' + X_2''|^m \end{cases} \tag{3}$$

Here, ϕ is the sum of two isotropic functions, which are symmetric with respect to X_i' and X_j''. X_i' and X_j'' are the principal values of the matrices, X' and X'':

$$\begin{cases} X_i' = \frac{1}{2}\left(X_{11}' + X_{22}' \pm \sqrt{(X_{11}' - X_{22}')^2 + 4X_{12}'^2}\right) \\ X_j'' = \frac{1}{2}\left(X_{11}'' + X_{22}'' \pm \sqrt{(X_{11}'' - X_{22}'')^2 + 4X_{12}''^2}\right) \end{cases} \tag{4}$$

Components of X' and X'' are obtained from the following linear transformation of the Cauchy stress:

$$\mathbf{X}' = \mathbf{L}'\boldsymbol{\sigma}; \quad \mathbf{X}'' = \mathbf{L}''\boldsymbol{\sigma} \tag{5}$$

where

$$\begin{bmatrix} L_{11}' \\ L_{12}' \\ L_{21}' \\ L_{22}' \\ L_{66}' \end{bmatrix} = \begin{bmatrix} 2/3 & 0 & 0 \\ -1/3 & 0 & 0 \\ 0 & -1/3 & 0 \\ 0 & 2/3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_7 \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} L_{11}'' \\ L_{12}'' \\ L_{21}'' \\ L_{22}'' \\ L_{66}'' \end{bmatrix} = \frac{1}{9} \begin{bmatrix} -2 & 2 & 8 & -2 & 0 \\ 1 & -4 & -4 & 4 & 0 \\ 4 & -4 & -4 & 1 & 0 \\ -2 & 8 & 2 & -2 & 0 \\ 0 & 0 & 0 & 0 & 9 \end{bmatrix} \begin{bmatrix} \beta_3 \\ \beta_4 \\ \beta_5 \\ \beta_6 \\ \beta_8 \end{bmatrix} \tag{7}$$

In Eqs. (5)–(7), $\boldsymbol{\sigma}$ is Cauchy stress and $\beta_1 - \beta_8$ are eight anisotropy coefficients. The procedure for solving $\beta_1 - \beta_8$ numerically was developed according to the method proposed by Barlat et al. [12]. In this study $m = 8$ since 5754O aluminum alloy is an FCC material.