International Journal of Mechanical Sciences 114 (2016) 315–329

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Characterization of anisotropic yield surfaces for titanium sheet using hydrostatic bulging with elliptical dies

Bruce W. Williams*, Kevin P. Boyle

CanmetMATERIALS, Natural Resources Canada, 183 Longwood Road South, Hamilton, Ontario, Canada L8P 0A5

ARTICLE INFO

Article history:
Received 7 October 2015
Received in revised form
15 March 2016
Accepted 27 May 2016
Available online 3 June 2016

Keywords:
Anisotropy
Yield surface
Titanium
Finite element
Bulge test

ABSTRACT

Progressive testing methods are required to accurately characterize the yield surface and large-strain plastic deformation behavior of anisotropic sheet metals. In the current work, hydrostatic bulging through elliptical dies with various biaxial ratios, coupled with full-field strain mapping, was used to generate sheet metal yield surface data for commercially-pure titanium and an exhaust grade titanium alloy. Supplementary characterization was provided by shear tests and tension test specimens taken at various orientations with respect to the rolling direction. The biaxial and tensile data were used to calibrate linear transformation-based anisotropic yield functions. To accurately apply the elliptical bulge tests results for yield function calibration, it was required to accurately calculate the hoop and longitudinal stresses at the pole of the ellipsoidal dome. The optimized yield function coefficients were calibrated for anisotropic response of the sheet metals to high levels of plastic deformation, up to 50%. Finite element simulations using the calibrated yield functions were then shown to provide accurate predictions of the elliptical bulge tests.

Crown Copyright © 2016 Published by Elsevier Ltd. All rights reserved.

1. Introduction

Increasingly, computational simulations, specifically finite element (FE) models, are being used to aid in the development of forming technologies of lightweight materials. It is important that material models utilized in FE analysis adequately describe the deformation response of the material. Many metals display anisotropic plastic deformation, particularly metals with a hexagonal closed packed crystal structure such as magnesium [1] and titanium alloys [2]. Hexagonal closed packed metals also potentially exhibit yield asymmetry, in which the material behavior in compression differs from that in tension. Several researchers have developed yield functions to describe the response of hcp materials. One of the most widely used yield functions for hcp materials was developed by [3], and will be referred to as CPB06. Plunkett et al. [4] extended the CPB06 to CPB06ex2, which essentially doubled the number of coefficients required to characterize the shape of the yield surface. The CPB06 yield function requires calibration of six coefficients to describe the deformation response of the sheet material in the absence of shear stresses at each level of effective plastic strain of interest. The CPB06ex2 requires the calibration of 12 coefficients at each level of effective plastic strain. Interpolation is used to obtain the yield surface response between effective plastic strains [5].

To characterize the anisotropic behavior of a metal several mechanical tests are required to calibrate the coefficients in the various yield functions. For sheet metal, important tests are the uniaxial tensile response in the rolling and transverse directions of the sheet. Additional tests in the normal, or through thickness, direction of the sheet can also be useful. The equi-biaxial stress versus strain curve, for which the shear stress is equal to zero, is also useful to calibrate the yield function. For an asymmetric material, compression data is required to calibrate the full yield surface, particularly in the compression-compression quadrant of stress space. To obtain compression data on a sheet, the technique detailed by [6] has been utilized in which the sides of a uniaxial specimen were constrained to prevent buckling. Effective plastic strains comparable to those at failure in tensile tests have been achieved.

Several multi-axial test techniques have been developed to characterize a materials response under different stress and strain paths to provide data to aid in the calibration of yield functions. Kuwabara [7] details the stress and strain paths obtained on high strength steel and aluminum sheet alloys from several multi-axial tests techniques including the hydraulic bulge test, the biaxial compression test, biaxial tension tests using cruciform specimens, and biaxial stress tests with tube bulging. Cruciform specimens have been utilized to generate data for tension–tension and tension–compression stress paths. A review of cruciform test methods has been given by [8]. This test has been useful for

---

* Corresponding author.
E-mail address: Bruce.Williams@NRCan-RNCan.gc.ca (B.W. Williams).

http://dx.doi.org/10.1016/j.ijmecsci.2016.05.022

0020-7403/Crown Copyright © 2016 Published by Elsevier Ltd. All rights reserved.

characterizing anisotropy of sheet metal around the point of initial yield [9]. However, even with complex cruciform specimen geometries it has been seen that instabilities occur at low levels of plastic strain leading to premature failure at lows strains [10]. More recent investigations have produced biaxial tensile data at higher levels of plastic strain. Teaca et al. [11] used biaxial cruciform specimens to produce data to generate anisotropic yield surfaces to about 15% major strain for deep drawing steel and AA1050 aluminum sheet alloys. Zhang et al. [12] used a biaxial test to generate data to calibrate an anisotropic yield function for AA5086 to about 12% major strain. Some of the highest levels of strain achieved using cruciform specimens have been reported by [13] for an AA5086 alloy. In this case, about 16% major strain was measured corresponding to an effective (von Mises) strain of 32%. Alternatively, tube bulging with end-feeding has been utilized to produce tension–tension and tension–compression stress states to higher levels of strain. Kuwabara and Sugawara [14] generated coefficients for the Yld2000-2d yield function for a 0.7 mm thick steel sheet that was bent and laser-welded into a tube and produced yield surface data up to 36% effective plastic strain. The data generated using the tube bulge test was compared to cruciform specimen data which was generated up to about 6% effective strain [14]. One disadvantage of the tube bulge test is that the sheet needs to be bent and welded into a tube. Mohr [15] developed a multi-axial test technique that subjected sheet metal to combine tension and shear loading. The data from the test was used to characterize the anisotropy of TRIP780 steel sheet to about 10% effective plastic strain. Recently, Revil-Baudard et al. [16] used Taylor impact tests to characterize high strain-rate anisotropy of a high purity α-titanium alloy up to about 20% effective plastic strain using the CPB06 yield function. The focus of the current work is on utilizing multi-axial test techniques to describe the plastic deformation response of the material. However, multi-axial test techniques are also of interest in the study of the fracture response of metal. Brünig et al. [17] detail a biaxial cruciform specimen with notched holes at the center of the specimen that was used to study damage and fracture under different stress states.

Although many tests have been developed to characterize anisotropy of metal, there is still the requirement to develop tests techniques to characterize anisotropy at higher levels of effective strain, specifically for sheet metal. Consequently, the purpose of the work is to develop a test methodology to characterize biaxial stress/strain response of sheet metal at high levels of deformation.

Elliptical bulge testing has been utilized for many years to characterize the failure response of sheet metal under different strain paths [18]. Rees [19] has shown that the hoop and longitudinal stress at the pole of the ellipsoidal dome can be predicted if the yield function and yield function coefficients are known and analytical equations were developed based on the Hill48 yield function. However, there is no data available in literature regarding using the elliptical bulge testing to generate data for yield function coefficient calibration. This is in part due to the calculation of the stresses at the pole generated during the elliptical bulge test. For the equi-biaxial bulge test, the resulting dome is a shell of revolution and standard equations from thin-membrane shell theory can be used to calculate the stresses in the dome [20]. Ragab and Habib [21] used equations to calculate the hoop and longitudinal stresses at the pole of the ellipsoidal dome based on assumptions reducing the problem to a shell of revolution. These equations were also utilized by [22] to calculate the effective stress versus strain behavior from elliptical bulge testing with digital image correlation (DIC) for a DC04 steel sheet with a thickness of 0.85 mm.

The current work focused on characterizing the yield surface response of two titanium sheet alloys, specifically during stretching. Wrought titanium alloys would be expected to have a strong sheet texture due to their hcp crystal structure leading to anisotropy as shown by [23] for a high purity titanium disc and by [2] for a titanium alloy sheet, similar to grade 2. Toussaint et al. [24] has detailed a yield surface for commercially pure grade 2 titanium sheet and Zhang [25] detailed a yield surface for a commercially pure titanium sheet, referred to as TA0, both based on the Hill48 yield function, but biaxial bulge data was not used to calibrate the yield function coefficients. Recently, Tritschler et al. [2] presented a yield function for a titanium alloy, comparable with Grade 2. Tensile and compressive data were utilized to calibrate a crystal plasticity model for the hcp material. Together with the experimental data, predictions from the crystal plasticity model were used to calibrate coefficients for CPB06ex2 yield function to effective plastic strain of 20%.

In the current work, the test data is analyzed using the equations derived from shell theory by [21]. The validity of these equations for the calculation of stresses at the pole of the bulged dome are determined by comparing the analytical stresses to stresses predicted from FE simulations of the elliptical bulge tests. Once the stresses are adequately predicted from the bulge test, the stress and strain are used, with supplementary tensile test data, to calibrate an anisotropic yield function. The calibrated yield functions are then verified by comparing the predicted dome shape from FE simulations with the measured dome shape from DIC.

The tensile stress versus strain response and corresponding hardening law used in the models for the titanium alloys is detailed in Section 2, along with the anisotropic yield function. In Section 3, the elliptical bulge test is described which generates experimental data in the tension–tension quadrant of strain space which will be used to calibrate yield function coefficients. Section 4 describes how, in general, to calculate the hoop and longitudinal stress in the elliptical dome were calculated and Section 5 details the hoop and longitudinal stress predictions specific to the titanium sheet alloys. The anisotropic yield functions for the two alloys are calculated and presented in Section 6. Section 7 details how the shear coefficients were determined by using the experimental data from tensile tests performed on specimens taken at various orientations relative to the rolling direction of the sheet and verified using data from shear test specimens. Finally, the yield functions are verified in Section 8 by comparing the domes measured from Digital Image Correction to the domes predicted from FE models performed using a user-defined subroutine for the anisotropic yield function.

2. Hardening law and yield function

Two titanium sheets were considered in the current work, commercially pure titanium (CP-Ti, B265 grade 1) and an exhaust grade titanium alloy with high temperature strength and oxidation resistance produced by TItanium METals Corporation (TIMET), which will be referred to as XT-Ti (0.5 Fe, 0.45 Si, 0.15 O, 0.1 C). The thicknesses for CP-Ti and XT-Ti were 0.92 and 0.93 mm, respectively. Uniaxial tension tests were performed on the CP-Ti and XT-Ti alloys. For both CP-Ti and XT-Ti tensile tests were performed at an initial strain-rate of at 0.001 s^{-1} at orientations of 0°, 22.5°, 45°, 67.5°, and 90° relative to the rolling direction (RD) of the sheet. The flow stress or hardening rule was based on the true stress versus true plastic strain response in the RD direction of the sheet. The hardening rule for the CP-Ti was given by [26],

$$\sigma_{flow} = A - (A - \sigma_{YS})\exp(-B\bar{\varepsilon}^{pC}) \tag{1}$$

where σ_{YS}=222.4 MPa, A=1550.7, B=0.320, C=0.520. The strain-rate sensitivity of the CP-Ti alloy was also given in [26] with

Download English Version:

https://daneshyari.com/en/article/783230

Download Persian Version:

https://daneshyari.com/article/783230

Daneshyari.com