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Applying a new constitutive model to analyse the springback behaviour of titanium in bending and roll forming

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ABSTRACT

This paper is an extension to previous work that dealt with the development of a strain path dependent constitutive model to describe the inelastic behaviour of Ti-6Al-4V at room temperature based on the homogenous yield function combined with the anisotropic hardening characteristics, the so-called HAH model. The present work is to apply and verify the accuracy of the proposed model in the finite element (FE) analysis of springback in bending dominated forming processes such as the V-die bending and the roll forming process. In addition, the model is applied to develop a greater insight into the nature of springback in the roll forming process where springback is generally lower compared to that found for simple bending. For this the hardening characteristics of Ti-6Al-4V were identified applying an inverse analysis approach in Abaqus Standard and the model used to describe the evolution of the anisotropic yield surface during non-proportional strain path deformation; this included the cyclic pure bending and cyclic tension–compression tests to generate experimental target curves. The constitutive model parameters were optimised to capture the cyclic behaviour of Ti-6Al-4V in both the pure bending and tension—compression and incorporated into the numerical models of a V-die bending test and a roll forming procedure to analyse springback.

The model achieved good agreement with experimental results and reproduced the lower springback observed in roll forming compared to simple bending. In contrast to this a conventional isotropic hardening model significantly overestimated springback for the roll forming process. This suggests that the lower level of springback observed in roll forming compared to V-die bending may be due to kinematic hardening effects. In addition, a lower level of accumulated effective stress and the presence of redundant shear strain was numerically observed in the bending regions of the roll formed section which also may have contributed to the reduction of springback. The results of this study suggest that for the accurate numerical prediction of springback in roll forming kinematic hardening effects need to be accounted for. For this the study presents an effective numerical approach and prove its applicability by numerical roll forming and V-die bending studies performed on high strength Ti-6Al-4V at room temperature and verified with experimental results.

1. Introduction

Titanium has been receiving increasing attention in lightweight construction [1]. In particular the major application of Ti-6Al-4V sheet finds in the aerospace industry [2] and the manufacturing of aircraft components [3]. Applications of titanium alloys in the automotive industry have been limited because of their higher costs compared to other competing materials such as steel, magnesium, and aluminium [4]. The automobile industry shows interest in the use of titanium to reduce weight and improve fuel efficiency [5] especially where high strength to weight ratio is essential [6]. Due to its high costs Titanium is currently not employed in high production vehicles [7] but as a result of its high corrosion resistance finds increased application in other fields [8] such as the chemical, and the marine industries [9]. Titanium sheet is generally difficult to form with conventional cold forming methods because of its poor ductility due to its HCP crystal structure, high material strength, low Young's modulus and large material anisotropy [10]. One of the major challenges in forming titanium sheet at room temperature is its large springback upon unloading when it is released from the forming tools [11]. Due to the limited formability of titanium sheet at room temperature bending processes are mostly used for the cold forming to structural components but are often limited to large forming radii [12]. Badr et al. [13] experimentally showed that Ti-6Al-4V sheet experiences significantly higher springback compared to Advanced High Strength Steels (AHSS) formed in V-bending [14] and roll forming [15] and related this to its higher material strength and lower Young's modulus. In the same study [13] it was observed that roll forming, a forming process

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increasingly used in the automotive industry for the manufacture of high strength structural components, allows the manufacture of tighter forming radii from Ti-6Al-4V sheet compared to the V-die bending process. In addition, the study showed experimentally that springback of Ti-6Al-4V in roll forming is significantly lower compared to that in V-die bending for the same profile shape formed. Weiss et al. [16] experimentally observed a similar trend in a previous study performed on AHSS and related this to the incremental nature of the roll forming process where the sheet is bent in successive roll stands. Other studies suggest that the lower springback in roll forming is the result of unwanted deformation in the section additional to that of transverse bending in the profile radius [17].

In order to achieve acceptable profile shape accuracy for Ti-6Al-4V, it is important to estimate the amount of springback with sufficient accuracy so that it can be incorporated into the tooling and process design. For this purpose, analytical equations that have been originally derived for bending are often being used to estimate the springback in roll forming. [18]. This is based on the assumption that the major deformation mode in roll forming is transverse bending [19]. Nevertheless, the studies mentioned above suggest that springback in roll forming and simple bending are not the same. Groche et al. [20] revealed that simple analytical equations generally give a weak representation of springback in the roll forming process. This has led to the increased application of numerical analysis to estimate shape defects in roll forming.

Up to now there are no numerical studies that have focused on analysing the material behaviour of Ti-6Al-4V sheet in bending dominated forming processes at room temperature. This is mainly due to a lack of accurate material models available to numerically represent the material behaviour of Ti-6Al-4V at room temperature [21]. Gilles et al. [22] applied the orthotropic asymmetry yield criteria CPB06, CPB06ex2 and CPB06ex3 in combination with a hardening model developed by Plunkett et al. [23] that accounts for distortional hardening due to texture evolution. However, this approach led to model predictions that were significantly different to those experimentally measured for Ti-6Al-4V in plane stress and for the in-plane material anisotropy. Gilles et al. [22] suggested that for an accurate description of the hardening behaviour of Ti-6Al-4V additional hardening parameters are required. This suggests that in forming applications where the sheet metal is subjected to non-proportional loading paths and stress reversals the associated distortional hardening behaviour has to be accounted for to numerically reproduce the material behaviour of Ti-6Al-4V. Recently, Barlat et al. [24] proposed a new constitutive model, the so called homogenous yield function-based anisotropic hardening (HAH) model, to describe the plastic deformation behaviour of Dual Phase (DP) steel and to account for the Bauschinger effect. Accordingly, Badr et al. [21] proposed a constitutive formulation based on the HAH model for Ti-6Al-4V alloy sheet. In this work the initial yield surface of the Ti-6Al-4V was experimentally measured for various stress states and fitted with the non-quadratic yield function YLD2000-2D. The determined yield function was then integrated into the formulation of the HAH model. The experimental verification with the in plane continuous tension/ compression and compression/tension tests showed that the model accurately describes the Bauschinger effect and the evolution of the yield surface with accumulated plastic strain [21].

The primary purpose of the present work is to confirm the applicability of the developed model for predicting the material behaviour of Ti-6Al-4V in bending dominated forming, in this case the V-die bending test and the roll forming process, with major focus on springback behaviour. Second focus is on numerically investigating material behaviour in the roll forming process and to develop a fundamental understanding of the origin for the lower springback tendency observed in roll forming compared to simple bending. For this, the proposed new model was implemented into Abaqus Implicit via a user-defined material subroutine “UMAT”. The mechanical properties of the Ti-6Al-4V were determined via the standard tensile test (Section 2.2). The characteristic of the constitutive hardening behaviour was fitted and optimized using an inverse approach including cyclic pure bending test as well as tension–compression tests over a full deformation cycle. The material model was then applied in a numerical analysis of the V-bending test and a roll forming application to investigate the effect of kinematic hardening on springback in both processes. For comparison the same analysis was also performed using a conventional, isotropic material model with the fitted non-quadratic yield function YLD2000-2D. The numerical springback results achieved with the new HAH model showed a very good agreement with the experimental measurement and captured the lower springback in roll forming compared to V-die bending that was observed in previous experimental studies performed on Ti-6Al-4V [13] and AHSS [16]. In contrast to this, the isotropic material model only achieved good springback correlation for the V-die bending test but significantly overestimated springback for roll forming. In addition a lower level of accumulated effective stress in the profile radius was observed in roll forming compared to V-die bending and there was a high level of redundant shear deformation in the flange and the profile radius of the roll formed profile. This indicates that the lower springback in roll forming compared to V-die bending may be the result of kinematic hardening effects combined with a high level of redundant strain accumulated in the roll formed profile. It further suggests that to achieve accurate numerical model accuracy for springback in roll forming a kinematic hardening model should be used. This knowledge in combination with the advanced material model introduced and proven by numerical and experimental analysis for roll forming and bending applications has significant value for industrial process development and optimisation and may enable the increased use of cold formed, high strength Titanium components.

2. Experiments

Details of the experimental trials used to characterize the uniaxial tensile properties, microstructure, V-die bending and roll forming at room temperature are given in previous experimental work performed by Badr et al. [13]. The following subsections only summarize the main procedure and the results of each test.

2.1. Material

The Ti-6Al-4V sheet investigated in this study has a thickness of 2.0 mm and was received as mill annealed (at 820 °C) cold rolled sheet stock. The microstructure consists of 93.86% volume fraction of α phase (hcp) and of 6.14% ± 0.6 β phase (bcc), with an average grain size of 1.3 ± 0.7 μm. The nominal chemical composition and detailed information with regard to the microstructure are given in [13].

2.2. Tensile and plastic anisotropic behaviour

Quasi-static tensile tests were conducted using a100 kN Instron tensile tester at room temperature according to Australian Standard AS1391-1991 [25]. Specimens oriented 0°, 45° and 90° to the rolling direction (RD) were cut and at least three repetitions were performed for each sample orientation; the cross-head speed was 2 mm/min. The test sample was clamped between the grips of the tensile tester after measuring the initial thickness t_i and the width w_i. During the test the applied force $F(N)$ was recorded by a load cell, while a video extensometer was applied to measure the axial engineering strain over a gauge section of 50 mm. The engineering stress–strain data at different directions was then converted to the corresponding true stress–strain $\sigma - \varepsilon$ curves which are shown for all three orientations tested in Fig. 1. Hooke's law (i.e. $\sigma = E.\varepsilon$) and the Swift hardening power law (i.e. $\bar{\sigma} = H(\varepsilon_0 + \bar{\varepsilon})^n$) were applied to fit the elastic and the plastic portions of the curves [26]. The corresponding tensile parameters are shown in Table 1. The 0.2% offset strain method was applied to determine the yield stress $\sigma_{0.2\%}$.

In order to determine the plastic anisotropy a second set of tensile tests was performed applying the same conditions as used above. Assum-