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Material parameter identification within an integrated methodology considering anisotropy, hardening and rupture

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ABSTRACT

The main focus of the present work is the development of a global procedure for a complete characterization of sheet metal behavior, including anisotropy, evolution of hardening and rupture. This efficient procedure involves the mechanical characterization, at room temperature and in quasi-static conditions, of the material up to large strains by evaluating the local strain field. The initial anisotropy, hardening and rupture of DC04 mild steel are characterized using a complex phenomenological model composed by the non-quadratic *Yld2004-18p* yield criterion combined with a mixed isotropic-kinematic hardening law and a macroscopic rupture criterion. For this purpose, an inverse methodology for material parameter identification is implemented based on several experimental tests considered as homogeneous and also, a mixed experimental-numerical approach to calibrate the rupture criterion is performed. In order to validate the obtained results, a deep drawing test, leading either to full drawing or rupture of the blank, is carried out. Digital image correlation is used to acquire additional data information in the deep drawing test. Strain fields at several stages of the deep drawing experiment are evaluated leading to a better comparison between the experimental observations and the results of the numerical simulation.

1. Introduction

Nowadays, finite element (FE) simulation of sheet metal forming processes plays a crucial role in the forming industry. From the economical point of view, FE simulation leads to a considerable decrease of the associated delays and costs with an optimal design of components (Kajberg and Lindkvist, 2004). The modeling of the mechanical behavior of sheet metals is a decisive input of these simulations, in order to obtain reliable numerical predictions of the forming processes. However, the success of these numerical predictions is much dependent on the quality of the constitutive model adopted, including the identification of the material parameters (Haddadi and Belhabib, 2012).

On one hand, the numerical simulations require the knowledge of the material behavior under several strain paths and strain amplitudes, corresponding to the paths and amplitude encountered during the forming process, e.g. (Zang et al., 2011). Thereby, within a phenomenological framework, the constitutive equations implemented in the numerical model must be able to reproduce this material behavior. On the other hand, the constitutive models include several material parameters that must be determined for each material and an efficient identification of these coefficients is essential in order to achieve reliability of the numerical predictions (Andrade-Campos et al., 2007). Within this general framework, the aim of the present work is the development of an efficient global procedure to characterize and model the mechanical behavior of sheet metals. This global procedure involves the mechanical characterization of initial anisotropy, evolution of hardening with strain and rupture for sheet metals.

Most of the sheet metals present anisotropic, and especially orthotropic, mechanical behavior. This anisotropy is mainly due to their crystallographic structure and the characteristics of the rolling process, being characterized by the symmetry of the mechanical properties with respect to three orthogonal planes. Anisotropic models based on a complex non-quadratic yield function are, usually, more suitable to accurately represent the material anisotropy of the sheet metal. Indeed, these yield functions involve a large number of material parameters, which gives a high flexibility to adjust to experimental data, e.g. *Yld2004-18p* function (Barlat et al., 2005), which is based on two linear transformations applied to the deviatoric stress tensor, depends on 18 coefficients for a three-dimensional stress state. The high number of coefficients directly

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allows for an excellent prediction of the mechanical behavior of highly anisotropic metals, such as AA2090-T3 aluminum alloy in (Yoon et al., 2006). This model has also proved its capability to provide an accurate prediction of the planar variations of the uniaxial yield stresses and plastic anisotropy coefficients as well as to predict the occurrence of six and eight ears in the process of cup drawing (Banabic, 2010).

Concerning the mechanical characterization of sheet metals along complex strain paths, cyclic deformation assumes a great importance in sheet forming since it characterizes the kinematic contribution to the hardening, related to Bauschinger effect and work-hardening stagnation phenomena. Taking into account these phenomena in the model leads to an improved prediction of some defects observed in sheet forming, such as surface distortion and springback (Cao et al., 2009). In fact, springback is one of the main problems influencing the final product quality in the case of forming process, and particularly for deep drawing. It has been proved that the reliability of the numerical prediction of springback increases due to the consideration of the Bauschinger effect (Chung et al., 2005). Recently, Chongthairungruang et al. (2012) investigated the influence of pre-deformation on the springback of high strength steel sheets. A modified S-rail forming test was used to evaluate the degree of springback of the steel sheets after a pre-strain. A more accurate springback prediction was achieved when using numerical models including kinematic hardening behavior.

Moreover, a reliable prediction of the material fracture is very useful in the design and optimization of forming process and products. The fracture behavior can be analyzed considering two different approaches: (i) uncoupled fracture criteria, which neglect the effects of damage on the yield surface of materials and (ii) ductile damage models coupled with plasticity, which take into account the degradation of the mechanical properties into the constitutive equations, up to the final rupture (Li et al., 2011). In this work, only the first approach is considered in a first step. The uncoupled fracture criteria are formulated considering an empirical or semi-empirical rupture parameter based on some macroscopic variables such as the equivalent plastic strain, principal (Cockroft and Latham, 1968) and hydrostatic stresses (Rice and Tracey, 1969), since these variables are the most relevant to fracture initiation and propagation. Although there is a limitation of not representing the deterioration of the mechanical properties related to damage, these fracture criteria are widely adopted due to their easy implementation into FE code and easy calibration (Wierzbicki et al., 2005). Indeed, several works were performed considering this kind of fracture criteria. Takuda et al. (1999) applied the combination of uncoupled fracture criteria with FE simulation in order to predict the fracture initiation and, consequently forming limits. The predictions were performed for a deep drawing experiment and accurate results were obtained by the authors. Ozturk and Lee (2004) presented a complete determination of FLD by using several uncoupled fracture criteria. For this purpose, tensile tests up to rupture and numerical simulations were used by the authors in order to calibrate the fracture criteria parameters. Zhalehfar et al. (2013) predicted the effect of strain path change on the forming limit diagram (FLD) at rupture by using a numerical approach and the uncoupled Cockroft–Latham (CL) fracture criterion. Björklund et al. (2013) also adopted the uncoupled CL fracture criterion and performed a comparison between experimental results coming from simple mechanical tests and FE simulations, to calibrate the criterion.

Recently, in order to promote a better mechanical characterization of sheet metal behavior, new strategies considering large strains and/or rupture by evaluating non-homogeneous strain fields have been developed. These new strategies are focused on the characterization of the sheet metal behavior using full field displacement measurements. Tarigopula et al. (2008) applied full field displacement measurements with the aim of identifying the material parameters of an elasto-plastic phenomenological model and calibrate Cockroft and Latham fracture criterion. In their methodology, strain hardening parameters are obtained from a standard uniaxial tensile test for small and moderate strains, while a shear test is used to determine the strain hardening for large strains and calibrate the fracture criterion. In this strategy, the numerical simulation of the shear experiment is performed up to strain value relative to experimental fracture and the maximum value of CL criterion is determined in the shear zone. Tardif and Kyriakides (2012) presented a systematic methodology to characterize the sheet metal behavior up to large strains by following the deformation in the necking area of a tensile test using digital image correlation (DIC) measurements. The authors used *Yld2004-18p* yield function to represent the anisotropy of an aluminum alloy by using the conventional tests recommended by Barlat et al. (2005) to identify the material parameters. The strain hardening of the material was iteratively adjusted by comparing the measured and calculated force–displacement response and validated by the corresponding measured strains and shape of the neck. An accurate numerical prediction of the necking section was obtained by this study. Güner et al. (2012) proposed a method to identify the planar anisotropy of sheet metals based on optical measurement of strain fields on a flat specimen with a varying cross-section. The material parameters of the constitutive model were determined by an inverse identification scheme comparing experimental and numerical strain distribution and force–displacement curves. The validation of identified parameters was performed by the drawing simulation of an industrial car hood geometry.

The above-referenced works present systematic methodologies that characterize only (i) sheet metal behavior up to large strains, or (ii) planar anisotropy behavior and material parameters validation or (iii) sheet metal behavior including rupture. In order to take all these phenomena into account, this work presents an integrated methodology that couples experiments, finite element simulations and modeling of the mechanical behavior of a sheet metal up to large strains including rupture, with an elasto-plastic model that involves a large number of material parameters. In this study, the anisotropy and hardening behavior of DC04 mild steel is reproduced by using a complex phenomenological model composed by the non-quadratic *Yld2004-18p* yield criterion combined with a mixed isotropic-kinematic hardening law. Additionally, the rupture behavior is characterized by the calibration of Cockroft and Latham fracture criterion. An inverse identification scheme, with an experimental database composed of conventional experiments, is implemented in order to identify the material parameters of the phenomenological model. For the calibration of CL fracture criterion, an experimental-numerical approach is performed. This one consists of the comparison of the experimental strain distribution, obtained by DIC measurements, of a tensile test carried out up to rupture with the numerical results obtained by FE simulation. With the purpose of validating the identified material parameters as well as the fracture criterion, a cup deep-drawing test leading either to full drawing or premature rupture of the blank is carried out. In this validation experiment, DIC measurements are also performed in order to obtain a more accurate analysis of the strain distribution and evaluate the capacity of the model to fully represent the mechanical behavior.

2. Constitutive model

Mixed hardening associated with *Yld2004-18p* yield criterion is used in this work to represent the mechanical behavior of the material up to rupture. The corresponding constitutive equations are detailed in this section. Equations were developed within a large