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A new strategy for the simultaneous identification of constitutive laws parameters of metal sheets using a single test

P.A. Prates *, M.C. Oliveira, J.V. Fernandes

CEMUC, Department of Mechanical Engineering, University of Coimbra, Rua Luís Reis Santos, Pinhal de Marrocos, 3030-788 Coimbra, Portugal

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ABSTRACT

An inverse analysis methodology for determining the parameters of plastic constitutive models is proposed. This involves the identification of the yield criterion and work-hardening law parameters, which best describe the results of the biaxial tensile test on cruciform samples of metal sheets. The influence and sensitivity of the constitutive parameters on the biaxial tensile test results is studied following a forward analysis, based on finite element simulations. Afterwards, the inverse analysis methodology is established, by evaluating the relative difference between numerical and experimental results of the biaxial tensile test, namely the load evolution in function of the displacements of the grips and the equivalent strain distribution, at a given moment of the test, along the axes of the sample. This methodology is compared with a classical identification strategy and proves to be an efficient alternative, allowing to avoid time-consuming tests, some of them hard to analyse and liable to uncertainties.

1. Introduction

The accuracy of the numerical simulation results in sheet metal forming depends on the selected constitutive model and the strategy used for the parameters identification [1–4]. Several phenomenological yield criteria (e.g. [5–10]) and hardening laws (e.g. [11–16]) have been proposed in order to improve the description of the plastic behaviour of metal sheets. Increasing the flexibility of the constitutive models is often associated with a larger number of parameters to identify. This requires a wide set of experimental tests and complex identification strategies. The constitutive parameters are usually identified from linear strain path tests (namely tensile, bulge and shear tests) with homogeneous deformation in the measuring region, using classical methodologies. As the rolling process makes the metal sheets anisotropic, different mechanical behaviours are expected for different loading directions and conditions. However, sheet metal forming processes are carried out with inhomogeneous deformation and under multiaxial strain paths. Therefore, limiting the characterization of the mechanical behaviour of metal sheets to a restricted number of tests with linear strain paths and homogeneous deformation can lead to a somewhat incomplete characterization of the overall plastic behaviour of the material [17].

From mechanical tests with heterogeneous strain fields it is possible to obtain a larger amount of information than the one found in case of tests with homogeneous strain fields. Therefore, heterogeneous strain fields can more suitably describe the influence of the strain path on the plastic behaviour of metals than homogeneous strain fields [18]. Material parameters obtained from homogeneous strain path tests are more appropriate for describing the material behaviour for one particular strain path, but can be unsuitable for other strain paths. To overcome this problem, it is necessary to develop tests allowing heterogeneous stress and strain fields and, eventually, strain path changes. The material parameters obtained through these tests will describe the overall mechanical behaviour of the material, taking into account the mutual influence of the various strain paths occurring in the sample, even if they are not fully appropriate for describing each particular strain path [18–20]. The material parameters obtained through such tests will be also suitable for describing the plastic behaviour of metal sheets during complex forming operations, in view of the heterogeneous nature of the deformation.

The increasing development of optical full-field measurement techniques for analysing heterogeneous strain fields, such as the digital image correlation (DIC) technique, has led to the development of new tests and methodologies for characterising the plastic behaviour of materials [21]. One possible approach consists on using inverse analysis methodologies, which are based on the determination of the material parameters that minimise the gap between numerically predicted and experimental test results [22]. These methodologies have been recently explored in the literature for the parameters identification of constitutive laws, by combining DIC measurements on the test samples with numerical simulation results of the test [18–20,23–25]. In this context, several works in literature, which propose the coupling of optical

* Corresponding author. Tel.: +351 239790700; fax: +351 239790701.
E-mail address: pedro.prates@dem.uc.pt (P.A. Prates).

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measurement results and inverse analysis methodologies together with numerical simulations results for the identification of constitutive laws parameters, are highlighted in the following.

Güner et al. [23] proposed an inverse analysis procedure for the identification of the Yld2000-2d yield criterion parameters corresponding to the initial yield locus of representative materials. This study, strictly numeric, uses a notched specimen submitted to a uniaxial tensile test, enabling strain paths near uniaxial tension. The required data for the inverse identification of the yield criterion parameters are variables such as the major and minor principal strains in the sheet plane, the tool force, and the equibiaxial yield stress value (which is assumed known *a priori*). The objective function is a combination of principal strain, tool force (at selected tool displacements) and equibiaxial yield stress differences between numerically generated and experimental reference values, and is minimised using the Levenberg–Marquardt algorithm. Different alternative orientations of the specimen with the rolling direction (0°, 45°, 90°) and configurations of the objective function (setting the strain, or tool force, components to zero) were considered to test the inverse procedure. The authors highlight the importance of including strain information on the objective function, which leads to an improvement on its minimisation.

Pottier et al. [18] developed a testing procedure based on the out-of-plane deformation of a sample, using stereo image correlation, for the simultaneous identification of the constitutive parameters of Hill'48 yield criterion and Ludwick work-hardening law of a pure titanium sheet. The identification procedure consists of a finite element update inverse method and the parameters are determined using Levenberg–Marquardt minimisation strategy, where the gap between experimental and finite element simulation results of the surface displacement fields and the global force is minimised. The authors highlight the importance of increasing the strain field heterogeneity for a better assessment of the material behaviour.

In another work, an inverse analysis methodology based on a least-squares formulation along with Gauss–Newton minimisation strategy was developed in order to simultaneously determine the constitutive parameters for Hill'48 yield criterion and Swift work-hardening law of a stainless steel [20]. In this case, the parameter identification is performed from the results of three different complex tests, all of them comprising heterogeneous strain fields: a uniaxial tensile test on a perforated tensile specimen, a uniaxial tensile test on a complex shaped specimen and a biaxial tensile test of a perforated cruciform specimen. Furthermore, the sets of parameters obtained from each test are applied to simulate the three complex tests previously described. This allowed concluding that a good practice is to develop the mechanical test in accordance with the sheet metal forming process in study [20]. This methodology was also adopted for performing the identification of Hill'48 yield criterion and Swift work-hardening law parameters of a mild steel, from the results of a biaxial tensile test of a perforated cruciform specimen [19]. This strategy allowed the determination of averaged parameters of the yield criterion and hardening law, which are better suited for the simulation of real sheet metal forming processes than the ones obtained from classical identification strategies [19].

The idea of testing cruciform specimens dates back to the 1960s [26]. Such tests show potential for application in characterising the plastic behaviour of materials, i.e. for estimating the parameters of the anisotropic yield criterion and the work-hardening law, namely: (i) strain paths ranging from uniaxial tension (in the arms region of the specimen) to biaxial tension (in the central region of the specimen), (ii) high strain gradients, from the central region of the specimen to the extremity of the arms and (iii) no sliding contact occurs with tools, avoiding friction. Also, by changing the load and/or the displacement ratio between the two perpendicular loading axes, it is possible to obtain different biaxial strain and stress states, in the central region of the specimen [27]. However, this test allows only attaining low values of equivalent plastic strain (close to those obtained in uniaxial tension) before instability occurs and no occurrence of out-of-plane shear stress is observed (which prevents the determination of the constitutive parameters associated with out-of-plane stress components, as usually occurs when using classical methodologies). The aim of this work consists in developing and evaluating the performance of an inverse analysis methodology for the identification of the plastic constitutive parameters (anisotropic yield criterion and work-hardening law), which describe the plastic behaviour of metal sheets, from a single biaxial tensile test of a cruciform specimen. The current approach aims to be simple, from an experimental point of view, and for this purpose one just analyses the load evolution during the test and the equivalent strain distribution along the axes of the specimen, at a given moment of deformation, as an alternative to follow the strain fields on the specimen surface during the test, as previously performed by other authors [19].

2. Numerical model

The geometry of the cruciform specimen was studied using finite element method results in order to reproduce, as far as possible, inhomogeneous deformation with the occurrence of strain paths that are commonly observed in sheet metal forming processes [28]. An overview of the optimisation procedure for the sample geometry is presented in Appendix A. Fig. 1 shows the selected geometry and the relevant dimensions of the cruciform specimen in the sheet plane. The 0*x* and the 0*y* axes coincide with the rolling direction (RD) and the transverse direction (TD) of the sheet, respectively. The cruciform specimen is submitted to equal displacements in both 0*x* and 0*y* directions, applied by the grips, as indicated in Fig. 1. The displacements along the 0*x* and 0*y* axes are measured at points A and B, respectively. The sheet thickness considered in this study is 1.0 mm.

The material is considered orthotropic. Due to geometrical and material symmetries, only one eight of the specimen was considered in the numerical simulation model. The specimen was discretised with tri-linear 8-node hexahedral solid elements with an average in-plane size of 0.5 mm and two layers through-thickness. Numerical simulations were carried out with DD3IMP in-house

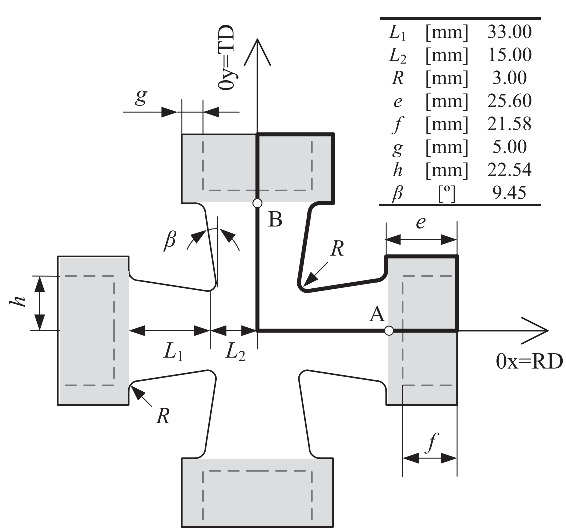

Fig. 1. Geometry and dimensions of the cruciform specimen. The grips, represented in grey, hold the specimen by grabbing it along the dashed grey lines. A and B represent the points for measuring the displacements, Δl.