Mechanical behavior of mild steel up to rupture: characterization and validation

Nelson Souto, António Andrade-Campos, Sandrine Thuillier

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N. Souto [a, b *], A. Andrade-Campos [a], S. Thuillier [b]

[a] Department of Mechanical Engineering
Centre for Mechanical Technology and Automation, GRIDS
University of Aveiro, Campus Universitário de Santiago
3810-193 Aveiro, Portugal

[b] Laboratoire d'Ingénierie des MATériaux de Bretagne (LIMATB)
Université de Bretagne-Sud, Rue de Saint Maudé BP 92116
56321 Lorient, France

[*] *nelson.souto@ua.pt*

Abstract. *In this work, the initial anisotropy and its evolution with strain, hardening and rupture of DC04 mild steel are characterized by using (i) a phenomenological constitutive model composed by the non-quadratic Yld2004-18p yield criterion combined with an isotropic hardening law and (ii) a macroscopic rupture criterion. For this purpose, an inverse methodology of material parameters identification is implemented and a numerical prediction of rupture is performed. The obtained results are validated in a cup deep-drawing benchmark.*

Keywords: inverse methodology; parameters identification; rupture.

1 INTRODUCTION

The main aim of this work consists on the modeling of the mechanical behavior up to rupture of DC04 mild steel. In order to do this, a constitutive phenomenological model as well as a macroscopic rupture criterion is considered.

The anisotropic plastic behavior of this steel is characterized by using the non-quadratic *Yld2004-18p* yield criterion combined with an isotropic hardening law. This yield criterion was selected due to the fact that it gives a very accurate description of the anisotropic properties, flow stresses and *r*-values in uniaxial tension [1]. In this way, the adopted phenomenological model is able to perform reliable predictions of deep drawing and springback results using numerical simulations. According to the authors [1], it is expected that the *Yld2004-18p* yield criterion predicts at least six ears in the deep drawing simulations of circular blanks.

Although the large flexibility and accuracy in the description of the yield surface, the *Yld*2004-*18p* yield criterion assumes more complexity than Hill's 1948 yield criterion, mainly due to the large number of material parameters that must be identified. Consequently, a large number of experimental tests is required for an appropriate material identification procedure.

The quality of the results coming from the numerical simulations depends on the quality of the input material parameters. Therefore, an efficient parameter identification procedure is mandatory in order to determine accurately constitutive parameters for a good description of the mechanical behavior of the material. In this way, an inverse methodology based on finite element method updating is developed to identify the material parameters of the studied DC04 steel. This identification framework is based on an interface program developed in Fortran that links the optimization software SDL [2] with the finite element code Abaqus [3]. This methodology compares the experimental data [4] of uniaxial tensile and shear tests at 5 different orientations with the rolling direction (RD) and bulge test with the results obtained numerically.

An objective function is defined in the least square sense and the Levenberg-Marquardt gradient-based optimization method is used for updating the material parameters in order to minimize the objective function value.

On other side, the study of the rupture phenomenon is of great importance in the forming industry, especially in automotive industry, due to the necessity of performing crash simulations and also predicting energy absorption in the materials. Thus, rupture ductility is also a relevant phenomenon, insofar consisting in the ability of a material to reach high amount of deformation without rupture. In addition, Fracture Forming Limit Diagrams (FFLD) based on rupture phenomenon are commonly studied in metal sheet forming simulation. Thereby, the rupture analysis and its mechanical characterization is also carried out. In this work, the Cockroft and Latham macroscopic rupture criterion [5] is adopted and it is predicted by performing uniaxial tensile experiments in the rolling direction using rectangular tensile specimens.
In order to validate the obtained results of the material identification process and rupture criterion, a cup deep-drawing benchmark up to rupture is performed experimentally and numerically and both types of results are assessed.

2 PARAMETERS IDENTIFICATION FRAMEWORK

The material parameters identification strategy is accomplished using stress-strain data results. This strategy consists on an inverse methodology since the aim is to determine input data that lead to a final desired result that is previously known. The solution of this problem can be found using an optimization method that leads to an iterative numerical simulation in order to minimize the difference between experimental and numerical data. Figure 1 illustrates the methodology applied for solving this parameters identification problem.

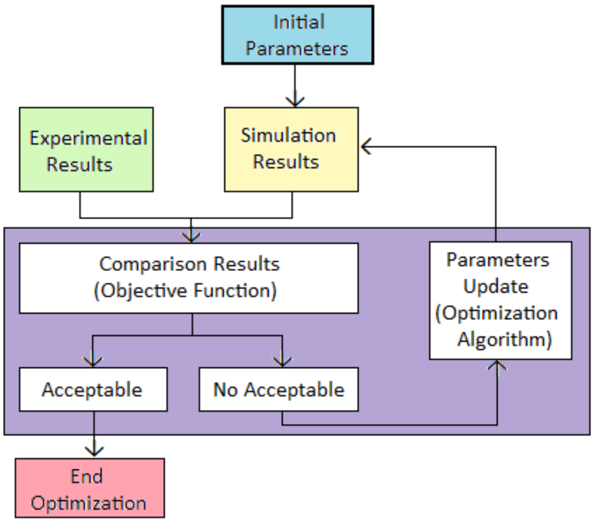


Figure 1: Methodology of the parameters identification framework.

From Figure 1, it is possible to understand that the inverse problem can be solved using an optimization process characterized by seeking a set of parameters for which the comparison between the experimental and the numerical stress-strain data results can be considered as satisfactory. For this purpose, an objective function that compares both results (numerically- and experimentally-based), as well as an optimization method to update the involved parameters, is required.
The optimization method adopted to update the material parameters during the identification procedure is the Levenberg-Marquardt (L-M) gradient-based algorithm [6, 7]. This algorithm is an evolution of the classic Newton method and calculates a search direction between the Gauss-Newton direction and the steepest descent direction. The L-M algorithm is characterized by alternating between a slow descent (when moved away from a minimum), and a quick convergence (when in the neighborhood of a minimum).
The main reason for the choice of L-M algorithm consists on the fact that this gradient-based algorithm has an excellent relationship between efficiency and required computational time. However, multiple solutions can be found when different starting points are used.
The experimental tests which characterize the studied DC04 mild steel consists on: uniaxial tensile and simple shear tests at 0°, 22°, 45°, 77° and 90° to rolling direction (RD) and the hydraulic bulge test. The experimental database used in the identification process is composed by the Cauchy stress-logarithmic strain/shear strain curves (σ-ε/γ) of all these experiments as well as the transverse strain-longitudinal strain (ε_{11}-ε_{22}) curves for the different uniaxial tensile tests and bulge test. Figure 2 shows the experimental and numerical σ-ε curves (left) for uniaxial tension and shear at 0°/RD and bulge test as well as ε_{11}-ε_{22} curves (centre) for uniaxial tension at 0°/RD and bulge

experiment obtained with the identified parameters. In addition, Figure 2 also shows the experimental and the numerical anisotropic r-values (right) obtained for the different uniaxial tensile tests.

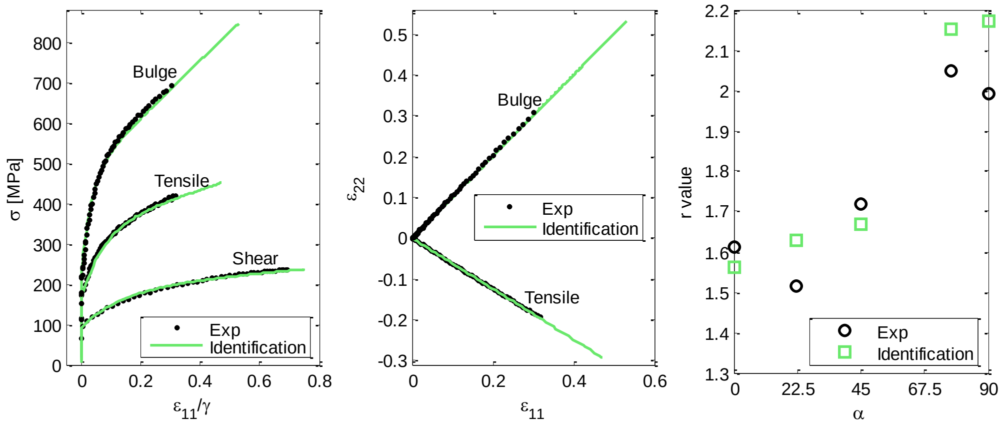
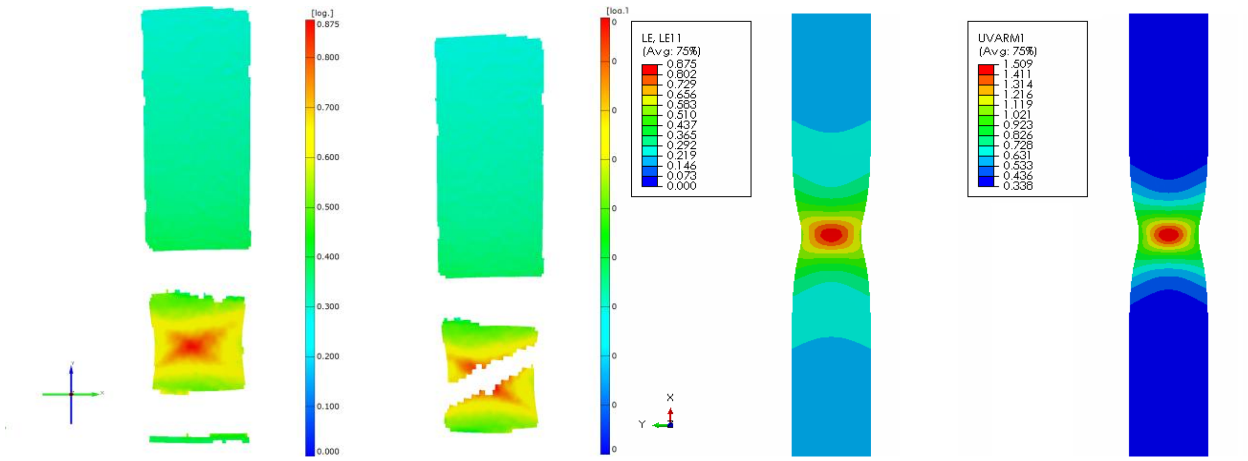


Figure 2: Experimental and numerical σ-ε curves for bulge and shear and uniaxial tension to 0°/RD (left), ε_{11}- ε_{22} curves for bulge and uniaxial tension to 0°/RD (centre) and anisotropic r-values of uniaxial tensile tests at angles α to the rolling direction (right) obtained with the identified parameters for DC04 mild steel.

3 RUPTURE CHARACTERIZATION

The rupture phenomenon is characterized by performing tensile test to RD up to fracture. The experimental data is obtained by using digital image correlation (DIC). This measurement system allows obtaining specific data which are very useful to understand and characterize the rupture phenomenon. Indeed, (i) ε_{11} isovalue just before rupture for the whole sample as well as the specimen fracture (depicted in Figure 3 a) and b), respectively), (ii) ε_{11} strain distribution along x (0°/RD) and y (90°/RD) direction in the center of the specimen and (iii) ε_{11} and ε_{22} average value in the critical zone just before rupture are the experimental data acquired. These data are essential to characterize the plastic instability due to the fact that the non-uniformity of the local strains in the critical zone are measured. Thereby, the validation of the numerical modeling is based on the previous experimental data and, in this way, the Cockroft and Latham rupture criterion can be accurately predicted through the numerical simulation of the experiment. Figure 3 c) and d) shows, respectively, the major strain and rupture criterion distribution at the moment of rupture obtained numerically.



a) b) c) d)

Figure 3: Major strain distribution (ε_{11}) of the experiment a) just before and b) just after rupture obtained experimentally by DIC ARAMIS system and, distribution of c) major strain (ε_{11}) and b) Cockroft and Latham criterion obtained by the numerical model just before rupture.

4 BENCHMARK TEST

The mechanical behavior of DC04 mild steel described numerically by the material parameters identified for the adopted constitutive model is evaluated and validated by using a cylindrical cup deep-drawing test. Process parameters leading to rupture during the process will be predicted by the numerical simulation and experiments will be carried out to validate this prediction. Figure 4 illustrates the numerical simulation of a cylindrical cup deep-drawing.

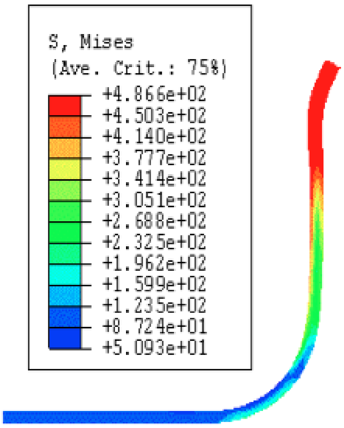


Figure 4: Deep drawing of a cylindrical cup. Process parameters leading to a rupture of the cup will be predicted and validated experimentally.

5 CONCLUSIONS

An accurate prediction of shape defects in numerical simulations of mechanical design of parts/processes is a fundamental task in order to decrease associated delays and costs of production. Therefore, a reliable mechanical behavior characterization up to rupture of sheet materials is of great importance for sheet forming industry. In this work, mechanical behavior characterization up to rupture is carried out for DC04 mild steel and the obtained results are validated by using a cylindrical cup deep-drawing benchmark.

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