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Design of an indicator to characterize and classify mechanical tests for sheet metals

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ABSTRACT

The aim of this paper is the design of a quantitative indicator able to distinguish, rate and rank different mechanical tests used to characterize the material behavior of sheet metals. This indicator is formulated considering (i) the strain state range, (ii) the deformation heterogeneity and (iii) the strain level achieved in the test, based on a continuous evaluation of the strain field up to rupture. In order to demonstrate the relevance of the proposed indicator, numerical simulations of classical as well as recent heterogeneous tests were carried out using as input the virtual mechanical behavior of DC04 mild steel. A complex elastoplastic phenomenological model including macroscopic rupture criterion was used. The performance of these tests was compared and their reliability on the mechanical behavior characterization was rated. By using the indicator, a ranking scale ordering the different tests is presented. The obtained results are validated by means of a material parameter sensitivity study. Finally, the proposed indicator can be applied to design new heterogeneous experiments that improve the mechanical characterization of sheet metals and, consequently, material parameter identification.

1. Introduction

It is well known that the success of finite element (FE) simulations of sheet forming processes is dependent on the quality of input data and, more specifically, on the material parameters associated to the material model adopted. Over the years, material parameters have been identified using classical mechanical tests, such as, uniaxial tension or simple shear, characterized by a rather homogeneous strain distribution over the gauge area of the specimen [1,2]. This kind of tests provides stress and strain data only for a fixed stress state, being then mandatory to carry out more additional classical tests when the adopted constitutive model depends on the information related to several stress states.

The development of new non-linear constitutive models with larger complexity led to an increase of the number of material parameters to be identified from experiments [3–6]. Thus, it imposes the use of an increasing number of classical tests and, consequently, the material parameters identification process becomes more expensive and time consuming.

Full-field measurement (FFM) methods, that have emerged in the last years (c.f. an overview in Grédiac [7]), directly provide displacement or strain data for all specimen geometry during the test. Such measurements on the overall surface of the specimen became a crucial tool for the analysis of more complex mechanical tests. Indeed, FFM methods overcome the drawback of the strain homogeneity of standard conventional tests by allowing the analysis of heterogeneous tests and monitoring complex strain fields such as the ones observed in real sheet forming processes.

Therefore, heterogeneous experiments aiming at the reproduction of the inhomogeneous and multiaxial strain paths encountered in sheet metal forming processes have been proposed. Most of the heterogeneous experiments available in the literature are based on the modification of (i) classical uniaxial tensile test [8–15] or (ii) biaxial tensile test using a cruciform specimen [16–18]. However, original tests based on a new design of the experiment have also been developed [19–22].

Concerning the geometry of heterogeneous tensile tests, it is mainly designed by (i) adding a hole [15,16], (ii) notching the specimen [8,10,11] or (iii) promoting a shear-like tensile zone [12,14].

Belhabib et al. [8] proposed a non-standard notched tensile test (HTT) for suitable identification of material parameters using FFM method. The specimen consists of a hybrid geometry between the classical tensile test (CTT) and the plane tensile test (PTT) and was designed with the aim of verifying (i) large heterogeneity of the strain in the gauge area, (ii) large strain paths diversity and (iii) good sensitivity of the strain fields to the material parameters. Comparing the tests, the authors verified that HTT presents large

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diversity of strain paths as well as better sensitivity of the strain fields and concluded that by using heterogeneous experiments, such as HTT, it is expected to identify parameters sets promoting a more reliable prediction of the material behavior.

Pottier et al. [15] compared the reliability of the material parameters identified from three different sample geometries. The tests exhibit increasing strain heterogeneities and consist of a classical uniaxial tensile, a tensile with a hole and a shear-like tensile. In order to evaluate the reliability of the three identified parameters sets, numerical simulations of a deep drawing experiment were compared with the experimental data. The results showed that a better numerical reproduction of deep drawing data was obtained with the parameter set identified from the shear-like tensile sample. According to the authors, it leads to the conclusion that the quality of material parameters identified improves and the required number of experiments decreases when the heterogeneity of the strain fields increases.

Nevertheless, since sheet metals undergo multiaxial stressing during forming processes, multiaxial loading experiments are highly desirable for the validation of the plasticity models used in numerical simulations [23]. Hence, it is of great interest to design new configurations for the cruciform specimen used in biaxial testing.

Teaca et al. [17] designed two types of cruciform specimens with the aim of obtaining a wide range of strain paths and a high sensitivity to material anisotropy. The specimens were developed in order to use the strain fields measured by a FFM method as input data for material parameter identification. An accurate description of plastic anisotropy is achievable with this strategy and, consequently, it leads to good predictions of strain distribution, forming limits and springback.

Additionally, Cooreman et al. [16] used an identification strategy of material parameters based on a heterogeneous biaxial test. In this work, a perforated cruciform specimen was used and the evaluation of strain field was carried out with digital image correlation (DIC) technique. The authors concluded that a heterogeneous strain field provided much more mechanical information than a homogeneous strain field, leading to a better characterization of the material behavior.

Among the original tests that introduced a new design for the specimen and the loading, the heterogeneous TIX test proposed by Pottier et al. [19] must be highlighted. This test is a new testing technique based on out-of-plane motion where the specimen is simultaneously deformed along two perpendicular tensile directions, two perpendicular shear directions and also in expansion, in different areas. This experiment was applied for material parameter identification purposes and, in order to check the quality of the identified parameters, a deep drawing test was carried out. By the comparison of the experimental and numerical results, the authors concluded that a single test can lead to the identification of a complete input parameters set of an anisotropic plastic model.

The above-mentioned works reveal the large benefits of using heterogeneous mechanical tests in the task of parameter identification of material models. Consequently, the design of new heterogeneous tests has been the focus of an increased number of studies.

Nevertheless, no defined criterion yet exists for designing new experiments. In addition, it is rather difficult to compare heterogeneous tests (or even heterogeneous and classical tests) and define the best one for the characterization of the material behavior. Therefore, it is crucial to determine if a given mechanical test provides more information, as well as with a higher reliability, for the characterization of the material behavior than another test. In this way, it will be possible to achieve the current aims for the mechanical characterization of sheet metals: (i) identify large sets of material parameters; (ii) improve the quality of the identified parameters and (iii) reduce the number of required experimental tests.

Therefore, the problem of ranking the information provided by the tests and of choosing the most suitable test for parameter identification is still unsolved. For this reason, the main goal of this work is the design of a quantitative indicator able to distinguish and rate different mechanical tests. The purpose of this indicator is also to guide the design process of new heterogeneous tests. In this way, a more straightforward, efficient and successful development of new mechanical tests can be achieved. The indicator can be used to compare new designs of tests with other existent tests and to query its reliability on the material behavior characterization of sheet metals.

Thereby, the formulation of an indicator focused on the mechanical behavior of sheet metal is presented and applied considering classical as well as heterogeneous tests. With the aim of validating the results obtained by the proposed indicator, an analysis of the material parameter sensitivity [8] for the chosen tests was performed.

2. Design of the indicator

In order to properly formulate the indicator, it is mandatory to define a list of the main features and mechanical phenomena presented in sheet metal forming that should be covered. Only in this way, will it be possible to design a quantitative indicator able to show that one mechanical test is more informative than another one. It must be noted that a mechanical test is considered more informative if a larger number of mechanical phenomena and stress/strain states are covered. Hence, the indicator must be an evaluation criterion rating the difference between tests and should include the following aims:

- Recognize and quantify all distinct strain states presented in the mechanical test, favoring tests that cover larger strain state range with a minor number of gaps.
- Analyze the deformation heterogeneity of the specimen during the test, promoting tests with large non-homogeneity.
- Evaluate the maximum strain achieved for the most important strain states, promoting the increase of these values.
- Quantify the average strain level, taking into account the geometry, and favoring large values of this average strain.
- Promote a continuous evaluation of the test up to rupture.
- Promote the unicity of the solution when identification strategies are used.

The listed features should be quantified to define the indicator and must be continuously evaluated during the test up to rupture. These can be arranged in the following two groups: (i) strain state range and heterogeneity and (ii) strain level.

The mechanical information conveyed by a test can be fully described by the strain and stress states. However, in order to be calculated both from experimental and numerical results, the indicator is solely based on information related to the strain state and stress invariants such as the equivalent stress, triaxiality ratio and Lode parameter were not considered in this work.

2.1. Features of the indicator

2.1.1. Strain state range and heterogeneity

As previously pointed out, several strain states are expected during sheet metal forming processes. Due to this reason, the strain state range of the test must be taken into account by the indicator. According to the continuum mechanics theory, a progressive deformation takes place continuously. Therefore, the strain state range of the mechanical test can be evaluated by the maximum and minimum strain state values achieved in the test.