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A numerical methodology to design heterogeneous mechanical tests

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ABSTRACT

Today, the constitutive behavior of a material is analyzed by means of mechanical tests and, consequently, reproduced using numerical models adjusted to each material through parameters. With the development of full-field measurement methods, recent material parameters identification strategies take advantage of the use of heterogeneous tests. Generally, the development of such mechanical tests is made by trial-and error approaches. In the present work, an innovative numerical optimization process for the design of heterogeneous tests is presented. The main goal is the design of a mechanical test able to characterize the material behavior of thin metallic sheets under several strain paths and strain amplitudes. Two different optimization approaches were proposed, namely (i) a one-step procedure designing both specimen shape and loading path by using rigid tools and (ii) a sequential incremental technique designing the specimen shape and the loading path of the specimen considering local displacements. The obtained results revealed that the numerical methodology proposed is capable for designing a single experiment able to fully characterize the several stress states encountered in sheet metal forming processes.

1. Introduction

In order to have a thorough characterization of the mechanical behavior of sheet metals, the design of different classical experiments was considered by the scientific community in the past, trying to reproduce individually the stress and strain states encountered in sheet forming processes [7,18,22,24,33]. More recently, thanks to full-field measurement methods [9] which provide a direct measure of displacement or/and strain data over the whole specimen surface, the design of non-classical experiments based on the heterogeneity of the strain field became the focus of several studies [3,12,21]. Alternatively to the classical experiments, where homogeneous stress and strain fields are provided, these heterogeneous experiments search for reproducing the stress and strain fields that generally occur in sheet metal forming operations, with only one test. Due to this, recent material parameter identification strategies [6,10,11,14,20,30,37] are based on the use of heterogeneous tests, with the purpose of (i) reducing the number of needed experimental tests and (ii) improving the reliability of the identified parameters.

The mechanical design of heterogeneous experiments needs the definition of sample geometry and boundary conditions, leading to a strain field that includes a large range of stress and strain states and amplitudes during the test. However, such a design should rely on no preconceived idea concerning the initial shape, boundary conditions and loading path of the experiment. Indeed, the use of existing experiments or specimen geometries in the quest for the best strain field is a constraint, since the assumption that such experiment or specimen geometry is the one that leads to the best results is made. However, for simplicity's sake, the most common specimen optimization approaches described in the literature are mainly based on (i) the shape improvement of existing classical experiments [3,8,31,32], usually by performing parametric studies for some geometrical parameters and (ii) trial-and-error attempts in the shape design of specimens inspired from previous experiments and empirical knowledge of the tests [4,21,25,34,35].

The classical experiments mostly used to re-design the specimen shape consist of the uniaxial tensile test [3,5,10–12,16,17,20] and biaxial tensile test using a cruciform specimen [6,15,23,31,37,38]. In the case of heterogeneous tensile tests, these tests are mainly modified by either adding a hole [6,20] or adding a notch [3,10,11] or promoting a shear-like tensile zone [12,17] in order to increase the heterogeneity of the strain field. In the case of the biaxial tensile tests, parametric studies are usually carried out on the geometrical dimensions of the cruciform specimen for many purposes such as to increase the failure strain [15], the formability [38] or the strain field heterogeneity [31].

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Concerning the shape specimen design based on trial-and-error attempts, twin bridge shear test [35] and TIX test [21] must be highlighted. On the one hand, the twin bridge shear specimen was based on the plane torsion test [36]. In this novel experiment, a round sheet specimen was modified by machining tangential slots, in order to obtain two shear bridges. On the other hand, the TIX test was inspired from Nakazima tests [19]. It was developed with the purpose of increasing the variety of strain paths. Such a task imposed the reproducibility of the boundary conditions, the minimization of friction phenomena and the existence of strain localization and, by trial-and-error attempts, a specimen generating shear, uniaxial and biaxial tensile zones was designed.

Among the works related with cruciform specimen optimization for biaxial tests, Makris et al. [15] developed an optimization procedure, with a cost function based on data extracted from the numerical strain field. Geometrical dimensions of the specimen were optimized in order to (i) maximize the region of strain uniformity in the biaxial loaded zone, (ii) minimize the strain concentration outside the area of interest and (iii) force the specimen failure to occur in the biaxial loaded zone.

Similarly, in the present work, an approach based on the strain field as well as shape and loading path optimization is considered. This innovative procedure was developed without taking into account any kind of specimen geometry or loading path of already existing experiments. Its main purpose is to understand what can be the best geometry and loading conditions that promote a strain field more sensitive to the mechanical behavior. To accomplish this, an optimization methodology based on a direct search method was developed in order to optimize the geometry as well as the loading path. A quantitative indicator [28], which rates the strain field of the experiment by quantifying the mechanical information of the test was used as a cost function, to guide the optimization process.

Parameterization of both shape and boundary conditions and optimizing them in an unconstrained way may necessitate a very large amount of parameters. Therefore, as a first step, two different approaches were considered, either using rigid tools to impose the specimen displacements, which limits the number of degrees of freedom, or controlling directly the local radial displacements. Moreover, displacements could be imposed in one step or in several steps. In this paper, two design strategies were developed:

- a one-step procedure optimizing both the specimen initial shape and the loading path by using rigid tools. The main advantage of this strategy is its resemblance with the experimental reality, since rigid tools are used for applying the displacement in a similar way as testing machines,
- a sequential incremental technique optimizing the specimen shape and the loading path considering local radial displacements. In this strategy, the optimization of the specimen shape was taken into account in the first step of the sequential optimization process while the loading path is subjected to optimization in all the sequential steps. This strategy consists of the most unconstrained optimization procedure developed in this work since (i) initial specimen shape, (ii) boundary conditions by means of local displacements and (iii) complex loading path by sequential steps are all designed by optimization.

With the aim of testing both strategies, some optimization processes were carried out in order to design heterogeneous tests. Moreover, the performance of these tests was compared with classical as well as modern experiments by using the quantitative indicator to rank the mechanical information provided by the strain field.

2. General characteristics

As a starting point and to limit the number of degrees of freedom, in order to save computational time, a symmetric model for the test, with only 2D displacements, was considered. Two symmetry conditions were imposed in the sheet plane and one in the sheet thickness (Fig. 1). The specimen geometry was defined by curve interpolation using cubic splines, which allowed a reduced number of design variables because only a few points, designated as control points, were needed to define them. Therefore, the shape of the specimen was controlled by 7 control points, defined at every 15° along the curved edge. The position of these control points was free during the optimization process, inducing modification and updating of the specimen geometry. The radial positions x_i, $i=1,\ldots,7$ of the control points were considered as design variables to be optimized. A different cubic spline was created between two consecutive control points, leading to a boundary shape definition composed by 6 continuous cubic splines.

During the optimization process, the design variables were updated in order to maximize the strain field information by decreasing a cost function defined in Section 4.2. The cost function was minimized using the Nelder–Mead direct search algorithm [13]. Direct search algorithms are not dependent on the gradient of the cost function and, usually, Nelder–Mead algorithm tends to be suitable for problems that are not smooth or have a number of discontinuities. For the design strategy with rigid tools, the maximum number of evaluations allowed for Nelder–Mead algorithm

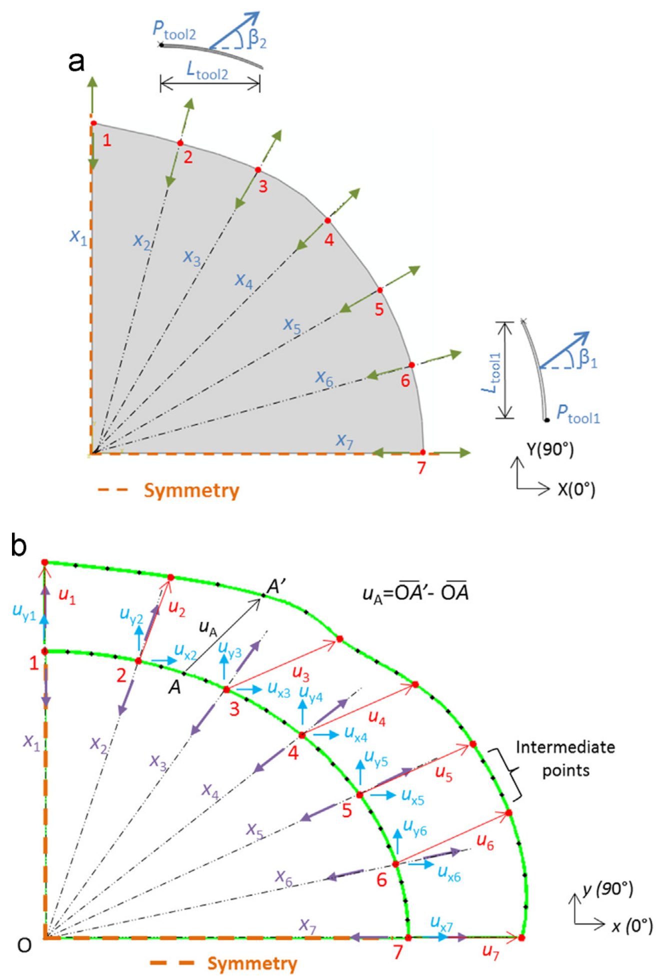

Fig. 1. Geometry of the specimen with the two symmetries in the sheet plane. Illustration of the displacements with (a) rigid tools and (b) local displacements.