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Improving the characterization of a hardening law using digital image correlation over an enhanced heterogeneous tensile test

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ABSTRACT

This paper presents the development and the implementation of an identification procedure of the parameters of a work-hardening law in the frame of large plastic deformation. This identification uses a finite element model updating (FEMU) method based on both the total force and the full-field strain measurements obtained during a single tensile test performed with a non-standard sample designed by the authors. This sample has the merit, as detailled in a previous study [1], of enhancing simultaneously: (i) the heterogeneity of the strain field within the whole gauge area of the sample, (ii) the diversity of strain-paths, (iii) and the sensitivity of strain maps to the hardening parameters. The stability of the identification algorithm was tested on virtual tensile tests performed on the same sample type by adding perturbations to numerical simulation results. The identification algorithm is robust at least up to relative noises of 10% and 25% on the force and strain, respectively. The results show that the identification seems acting as a filter by eliminating nearly all added perturbations. The identification performed on a real test led to a good agreement between simulation and experiment on both strain fields and force–displacement curve. Finally, the improvement of the prediction of strain maps was validated by performing a tensile test on another non-standard sample [2] which was not included in the identification protocol.

1. Introduction

The use of numerical simulation in general and finite element analysis (FEA) in particular has become a mandatory step of material processing optimization. The quality of these simulations depends on the choice of a well suited constitutive law with appropriate identification of its parameters for the studied material. Significant work was done in the identification area and the adopted strategies can be classified in the following three categories:

(1) identification of the mechanical model parameters using stress *vs.* strain raw data obtained with classical mechanical tests (*e.g.* tensile tests, simple shear, …) performed on standard specimens. The samples are designed to ensure a good homogeneity of the mechanical fields in the gauge area [3,4]. The geometry of these samples is not taken into account during the identification;
(2) identifications which use the total applied force *vs.* total elongation of the sample. As the mechanical response depends on the shape of the sample, for each identification iteration a numerical simulation using the real shape is performed to calculate the cost function to minimize. This simulation can be a finite element analysis [5–7] and in this case the identification method is called total force based finite element model updating (TFB–FEMU);
(3) the recent increase in the use of full-field measurements methods (e.g. strain, temperature) brought the development of numerous identification methods which use both experimental measurements of the applied force and strain maps.

This last category of methods offers the opportunity to use a huge amount of experimental data coming from the strain maps (*i.e.* thousands of measurement points). The development of these methods of identification started two decades before with applications to the measurement of elastic parameter or a field of damage parameter. These methods are briefly listed below:

- the virtual fields method (VFM) [8–10] initially developed by [11];
- the equilibrium gap method (EGM) [12,13];
- and the finite element model updating method (FEMU) which was implemented in the frame of the present study.

The number of published works on these methods remains weak due to the fact that performing an identification of model parameter requires to master both full-field measurement and an

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identification technique. Some studies used a very low number of measurement points (*i.e.* not enough for mapping a strain field) for the identification of the parameters of the hardening law [14,2], or used full-field strains for the calibration of elastic constants [15] and/or hardening parameters in the frame of small plastic deformation [16]. Other studies (*e.g.* [17]) used only the comparison between measured strain fields and those obtained with the finite element analysis without taking into account the force–displacement response of the material.

Among strain measurements methods that were implemented during the last three decades one can list:

- grid method [18,19,9,20];
- interferometric Moiré method [21,22];
- and digital image correlation (DIC) technique [23–25].

This latter technique has been widely used last decade in several applications [26–29]. The advantages and implementation of DIC technique are addressed in literature [30,31].

The objective of the present work is to carry out an identification of the model parameters that describes the plastic hardening behaviour of a dual-phase steel. Both force–displacement and measurements of strain fields in the same ranges than those occurring in sheet metal forming process are used. In Section 2, the mechanical model that describes the material behaviour is presented. The forward problem is addressed in Section 3. Section 4 deals with the inverse problem and the cost-functions definition as well as the chosen optimization procedure. The identification is based on a cost function to minimize which is defined by a weighted least squares deviation between finite element simulation results and experimental measurements. The feasibility and the robustness of the identification technique is also studied in this section using virtual strain maps and tensile force data obtained by adding perturbations to a numerical simulation results. Section 5 presents the material parameters identification using a real tensile test data. The validation of the improvement of the prediction of strain maps using a tensile test on a different non-standard sample developed by Meuwissen et al. [2] is presented in Section 6. The paper is ended with some concluding remarks.

2. Mechanical model of the studied material

2.1. Studied material

The studied material is a dual-phase steel DP600. This steel family is generally obtained by cold rolling process on annealing lines including a cooling stage [32]. Its chemical composition is given in Table 1.

2.2. Yield criterion

The studied DP600 steel was assumed to have standard rate independent elastic–plastic behaviour. The elasticity is linear and isotropic with Young's modulus $E=200$ GPa and Poisson's ratio $\nu=0.3$. The yield criterion was considered as quadratic and anisotropic [33]. It can be written in the orthotropic frame of the metallic sheet in the following form:

$$F(\boldsymbol{\sigma},\varepsilon^p)=\overline{\sigma}-Y(\varepsilon^p)=0, \tag{1}$$

with

$$\overline{\sigma}^2=F(\sigma_{yy}-\sigma_{zz})^2+G(\sigma_{zz}-\sigma_{xx})^2+H(\sigma_{xx}-\sigma_{yy})^2 + 2L\sigma_{yz}^2+2M\sigma_{zx}^2+2N\sigma_{xy}^2, \tag{2}$$

where $\boldsymbol{\sigma}$ is the Cauchy stress tensor, $\overline{\sigma}$ is the Hill'48 equivalent stress, σ_{ij} are the stress tensor components in the orthotropic frame and ε^p is the equivalent plastic strain. The axes x, y and z represent the rolling, transverse and normal directions of the metal sheet, respectively. The Hill's coefficients F, G, H, L, M, and N were identified [34] using the $r(\alpha)$ raw data, where r is the Hill's coefficient of anisotropy and α is the angle between the direction of tensile test loading and the rolling direction. The values obtained for the studied steel are $F=0.490$, $G=0.504$, $H=1-G=0.496$, and $N=1.27$. For metallic sheets, the parameters M and L are not easily accessible because of the relative small thickness of the specimens. So they are usually taken equal to 1.5.

2.3. Work-hardening law

The work-hardening is assumed to be isotropic. Its evolution is explicitly given by a Swift law:

$$Y(\varepsilon^p)=Y_0\left(1+\frac{\varepsilon_p}{\varepsilon_0}\right)^n. \tag{3}$$

The hardening parameter vector $\mathbf{P}=(P_1,P_2,P_3)=(Y_0,\varepsilon_0,n)$ was already identified in a previous study [34] starting from classical average stress and average strain raw data obtained from tensile and simple shear tests. The obtained values of these parameters are: $\tilde{Y}_0=330$ MPa, $\tilde{\varepsilon}_0=1.66\times10^{-3}$ and $\tilde{n}=0.187$. In what follows, it is referred to these values as the "reference hardening parameter" $\tilde{\mathbf{P}}=(\tilde{P}_1,\tilde{P}_2,\tilde{P}_3)=(\tilde{Y}_0,\tilde{\varepsilon}_0,\tilde{n})$.

3. Forward problem

3.1. Shape of the tensile test sample

As mentioned above, it was shown by the authors that the shape of the adequate sample shape to be used for the identification of the material parameters starting from the force-displacement curve and the kinematic fields has to satisfy three criteria: (i) the area of the sample with strong heterogeneity must cover the largest part of the gauge area in order to reduce data redundancy, (ii) the same sample should enhance the diversity of the strain-paths, (iii) and the most important criterion is that the strain maps should be more sensitive to the material parameters than it is the case for standard specimen. These criteria were studied on three different shapes of tensile test samples [1] and the authors shown that the heterogeneous tensile test (HTT) sample depicted in Fig. 1 presents the best strain heterogeneity, strain-path diversity, and strain fields sensitivity to hardening parameters with respect to the two other sample shapes (*i.e.* standard and plane tensile tests).

Table 1
Chemical composition of the dual-phase steel (DP600) used in this study.

Element	C	Mn	P	S	N	Si	Cu	Ni	Cr	Al	Mo	Ti
wt.(%)	0.122	1.441	0.011	0.005	0.004	0.321	0.029	0.022	0.209	0.038	0.055	0.008