Determination of the plastic strain by spherical indentation of uniaxially deformed sheet metals

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Keywords: Spherical indentation, inverse analysis, deformed sheet metals, plastic strain.

Abstract

This work consists of determining the plastic strain value undergone by a material during a forming process using the instrumented indentation technique (IIT). A deep drawing steel DC01 is characterized using tensile, shear and indentation tests. The plastic strain value undergone by this steel during uniaxial tensile tests is determined by indentation. The results show that, the identification from IIT doesn't lead to an accurate value of the plastic strain if the assumption that the hardening law follows Hollomon law is used. By using a F.E. method, it is shown that using a Voce hardening law improves significantly the identification of the hardening law of a pre-deformed material. Using this type of hardening law coupled to a methodology based on the IIT leads to an accurate determination of the hardening law of a pre-deformed material. Consequently, this will allow determining the plastic strain value and the springback elastic strain value of a material after a mechanical forming operation.

1. Introduction

The use of new grades of materials (aluminum alloys, Dual Phase, TRIP), aiming for lighter automobile structures, complicates the computer codes prediction of the springback phenomenon after stamping. The springback phenomenon depends on the material, the deformation path and the cumulative plastic deformation level in severely deformed regions. To obtain plastic strain values of deformed metal sheets locally, it is proposed to use the instrumented indentation test. This test consists of driving an indenter in the studied material and using the obtained force-depth curve, F-h, to determine the mechanical properties of the material. The indentation test has the advantage of identifying, very locally, the parameters of the hardening law of a material. However, this test has the disadvantage of having a complex deformation field developed under the indenter. So far, the obtained results show that the identification of the representative strain values from indentation allows obtaining hardening laws very similar to those obtained by classical mechanical tests such as tensile or shear tests [1], [2], [3]. The present study consists of using the indentation test to determine the plastic strain value and the hardening law of a DC01 deep drawing steel pre-deformed previously by a tensile test. This will lead to predict locally, using the IIT, the springback of a material after a mechanical forming operation.

2. Characterization of the as-received sheets.

In this experimental study, a cold rolled mild steel sheet DC01 is used: 3 samples were prepared for each direction: 0° (rolling direction), 45° and 90°. Tensile tests were performed on specimens with rectangular cross section of 10mm x 2mm and gage length of 80mm. The deformations were determined using a high speed camera that follows the evolution of the distance between two points aligned in the loading direction. For each direction, the arithmetic mean of the 3 stress-strain curves is considered as the hardening law of the material.

In addition to tensile tests, shear tests were conducted on the DC01 steel sheets. The dimensions of the shear samples are 50mm x 18mm x 1mm. From the shear stress and the angular deformation values, the Von Mises stress values and the corresponding equivalent strain values were determined and compared to the values of the stresses and strains obtained by the uniaxial tensile test. The DC01 hardening curves obtained by tensile and shear tests are shown in Fig.1. DC01 steel presents some anisotropy in tensile behavior and shows some difference between tensile behavior and shear behavior.

Hardening laws of as-received sheets DC01 are characterized by indentation using an experimental bench developed in our laboratory [4], [5]. These laws will be used as a reference when identifying pre-deformed sheets using the indentation technique. The indentation tests were performed with a rounded tip carved in bulk tungsten carbide indenter of 0.25 mm nominal radius. Mechanical polishing with abrasive paper (grade 1200) is performed on each surface of the sample to remove the surface defects. Four indentation tests are conducted on each sample to verify the reproducibility of the tests.

For the identification from IIT, it is assumed that the hardening law follows the modified Hollomon law written as follows:

$$\begin{cases} \sigma = E.\varepsilon & \text{(Hooke)} \quad \text{if } \varepsilon \leq \sigma_Y/E. \\ \sigma = \sigma_Y^{1-n}.E^n.\varepsilon^n & \text{(Hollomon)} \quad \text{if } \varepsilon \geq \sigma_Y/E. \end{cases} \tag{1}$$

With E the elastic modulus (E=210 000 MPa), σ_Y the yield stress and n the work hardening exponent.

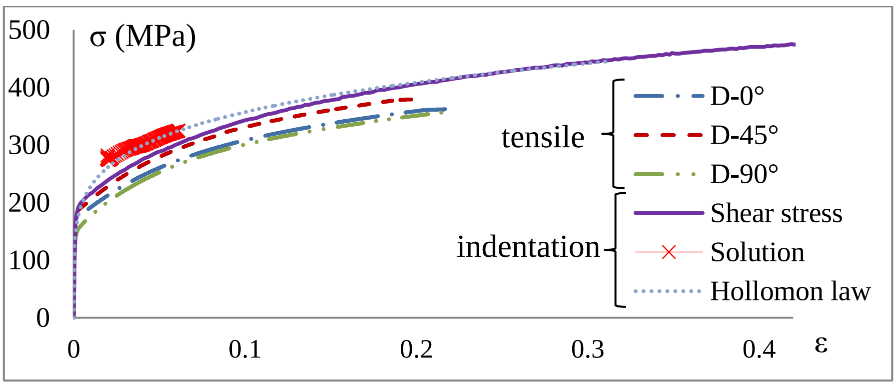

Fig. 1 : Hardening laws of the DC01 obtained from tensile and shear tests and identified from IIT.

The identification method, presented in previous articles, consists of determining the values of σ_Y and n that minimize the difference between the experimental indentation curve and the numerical curves of a previously established database [3], [6]. In Fig. 1, the hardening laws of the DC01 identified from IIT are compared to the hardening laws obtained from tensile and shear tests.

The crosses in Fig. 1 represent the σ-ε couples obtained from the indentation test. The highest σ-ε couple is the most accurate. Therefore, the σ_Y and n parameters obtained for this σ-ε couple are used to determine the Hollomon law of the material (dotted curve in Fig. 1). This law will be considered below as the hardening law of the as-received steels. Fig. 1 shows that the hardening curve identified by indentation test is higher than those obtained by shear and tensile tests on a plastic deformation range between 0 and 0.3. As will be shown later, this result is also due to the fact that the Hollomon law used in the identification does not follow perfectly the hardening law of the studied steel sheets.

3. Characterization of the pre-deformed sheets assuming that the hardening law is a Hollomon law.

A plastic pre-deformation was applied by a uniaxial tensile test on the DC01 steel sheets. Nine samples were prepared. 3 samples were deformed in every direction: 0° direction (rolling direction), 45° and 90°. For each of these directions, the sheets have undergone plastic strain values of about 3, 6 and 12%. Before indentation, as for the as-received sheet metal, a mechanical polishing with an abrasive paper (Grade 1200) was performed on each side of the plastically deformed sheets. Using the same method as for the as-received sheets, the new hardening law of the deformed steel sheets is obtained. Fig. 2 shows the solution obtained for a DC01 sheet deformed following the rolling direction of about $\varepsilon_{p-initial} = 5.9$ %

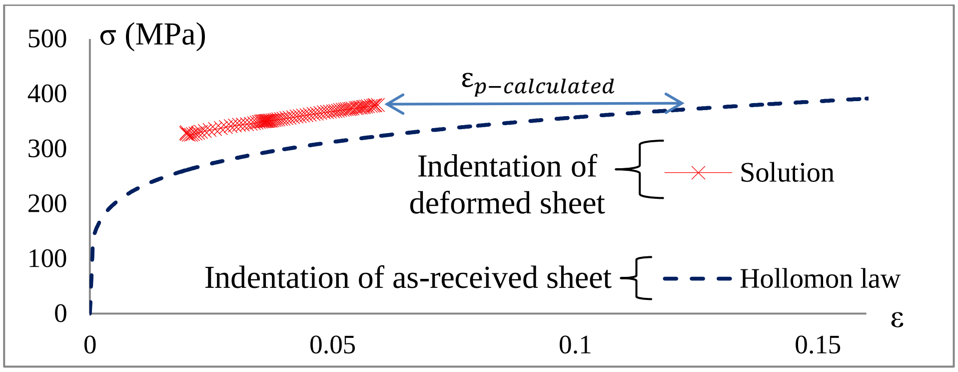

Fig. 2 : Determination of the plastic strain value from instrumented indentation test for a DC01 sheet deformed following the rolling direction of about $\boldsymbol{\varepsilon_{p-initial} = 5.9}$ %.

Using the results of the identification from IIT, it is proposed to estimate the plastic strain value undergone by the metal during the tensile test. The proposed procedure is to offset horizontally the highest σ-ε couple (and therefore the most precise couple) so that it superimposes on the hardening law of the as-received steel (see Fig. 2). The value of the deformation obtained is then considered as the value of the plastic deformation undergone by the sheet during the tensile test. For the case presented in Fig 2, a plastic deformation of 7.7% is determined by indentation while the actual value undergone by the sheet is about 5.9%. From the value of the plastic strain determined by indentation, the springback elastic strain at the end of the tensile test is estimated to be 0.16%. The real value of the springback elastic strain measured at the end of the tensile test is equal to 0.144%, which gives an overestimation of the springback of 9.9% when using the indentation results. The overestimation noted for the case of Fig. 2 is also observed for all of the DC01 sheets deformed by the tensile test.

To understand the overestimation of the plastic strain identified by indentation, a numerical study is presented in the following section.

4. Numerical study of the identification of the hardening law of a pre-deformed steel using IIT.

4.1. Characterization with a Hollomon hardening law: For this numerical study, the hardening law of the as-received studied sheet is roughly similar to that of the as-received sheet steel DC01. For this material the hardening law follows the modified Hollomon law given in Eq. 1 and the parameters of this law are: E = 210 000 MPa, σ_Y= 84,75 MPa and n = 0.25. From indentation simulations carried out with the FE model presented in previous articles [6], the hardening law of the material was identified by using the methodology followed in the previous sections. Fig. 3 shows that the use of the indentation test and the proposed method leads to a good prediction of the hardening law of the material when its hardening law follows the Hollomon law.

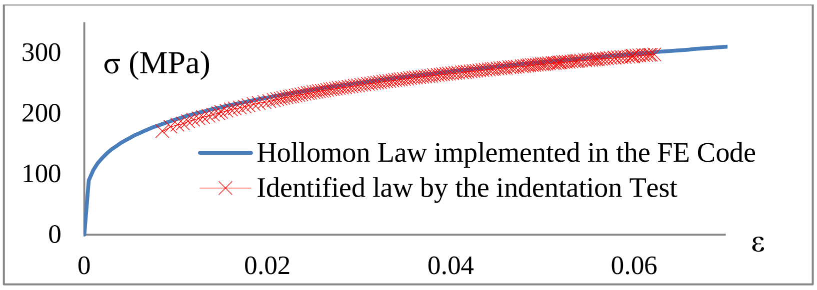

Fig. 3: Hardening law identified from IIT for a material of Hollomon hardening law (Eq. 1).

Considering that the studied material undergoes a plastic strain of 9%, the hardening law of the deformed material is shown in Fig. 4. From the indentation simulation carried out for the deformed material, the identification of the hardening law, performed with the methodology used in the previous chapters, leads to the result given in Fig. 5. As shown in Fig. 5, an overestimation of the identified hardening law is obtained at the location of the most accurate σ-ε couples (crosses in Fig. 5 located in the range 0.02 < ε <0.065). The offset of the highest σ-ε couple so that it superimposes on the hardening law of the as received steel leads to an overestimation of the plastic strain undergone by the material studied (result similar to the experimental result).

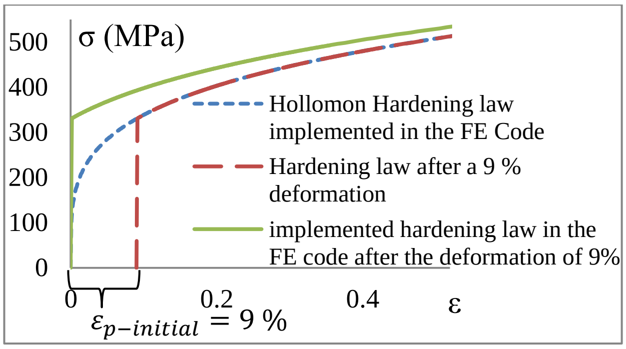

Fig. 4: Hardening laws of the studied material before and after plastic strain of 9%.

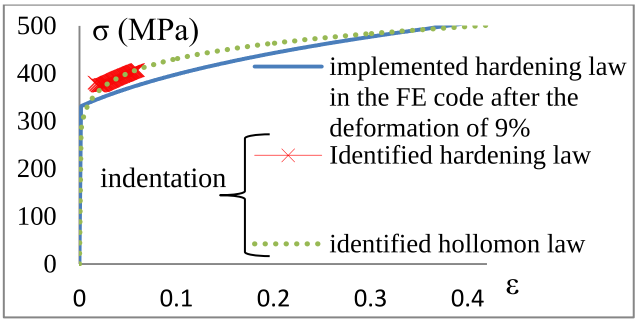

Fig. 5 : Identification of the hardening law of the studied material using the numerical indentation test and the previously mentioned method.

Fig. 6 shows that the overestimation of the hardening law on the strain range 0.02-0.065 is due to the fact that the hardening law of the deformed material does not follow the Hollomon law (eq. 1). This figure also shows that the Voce hardening law represents more precisely the hardening law of the material plastically deformed of about 9%. In the following section, it is proposed to use the Voce hardening law in order to obtain a more accurate assessment of the value of the plastic strain undergone by the material.

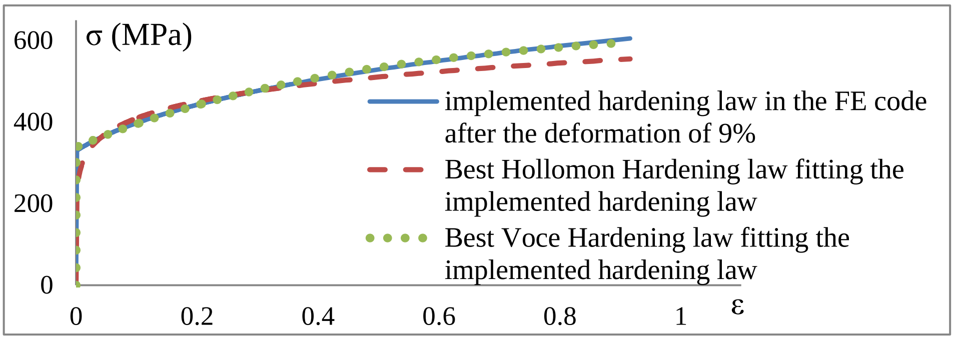

Fig. 6: Fit of the hardening law of the deformed material by a Hollomon law (Eq. 1) and a Voce law (Eq. 2).

4.2. Characterization with a Voce hardening law: The hardening law of the deformed metal follows the Voce hardening law presented as follows:

$$\begin{cases} \sigma = E.\varepsilon. & \text{(Hooke)} \quad \text{if } \varepsilon \leq \sigma_Y/E. \\ \sigma = \sigma_Y + Q * (1 - \exp(-b * \varepsilon_p)). & \text{(Voce)} \quad \text{if } \varepsilon > \sigma_Y/E. \end{cases} \quad (2)$$

With σ_Y the yield stress; Q (MPa) the maximum expansion of the load surface and b a parameter which controls the curvature of the hardening law.

In the aim of identifying, by indentation, the three parameters $(\sigma_Y\,; Q; b)$ of the Voce hardening law of the plastically deformed material of 9%, an inverse analysis optimization using an optimization software coupled with an FE code was performed. It has been shown in several references [7], [8], that the inverse analysis method doesn't always provide a unique solution for a non-linear problem. Therefore, the identification of three parameters of the Voce hardening law from IIT can lead to a problem of uniqueness of solution. To avoid this problem, we propose to choose a starting point close to the expected solution for the inverse analysis. Thus, we choose, as a starting point, the parameters $(\sigma_Y\,; Q; b)$ of the Voce hardening law which is closest of the identified Hollomon law (Hollomon law identified with the method given in references [3], [6] and shown in Fig. 5). A minimization procedure gives σ_Y= 352.16 MPa; Q = 122.07 MPa; b = 10.58 for the starting point. The minimization algorithm used for the inverse analysis procedure is a BFGS (Broyden-Fletcher-Goldfarb-Shanno) quasi-newton algorithm [9] with the cost functional given by:

$$E_1\left(\frac{h_{max}}{R}\right) = \frac{1}{h_{max}} \int_0^{h_{max}} (F_{ref} - F_{num})^2 dh. \quad (3)$$

Where h is the penetration depth of the indenter in the sample, h_{max} is the maximum penetration, F_{ref} is the load obtained for the plastically deformed material of 9% and F_{num} is the load obtained with the FE code during each iteration.

Fig.7 shows the hardening laws of the as-received material and the deformed material, the Voce starting law used for the inverse analysis optimization and the hardening law corresponding to the solution obtained by inverse analysis.

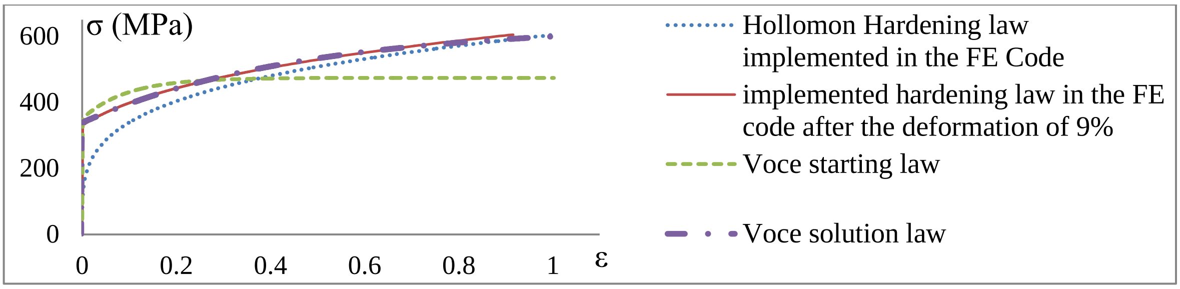

Fig. 7: Hardening laws of the studied material before and after deformation as well as the Voce starting law and the Voce solution law.

Fig. 7 shows that the use of the Voce hardening law lead to a correct identification, from IIT, of the hardening law of the plastically deformed material. In order to determine the plastic strain undergone by the material, a simple offset allows superimposing the identified hardening law on the hardening law of the as-received material. This offset leads to the determination of a plastic strain of 9% which corresponds to the value of the plastic strain undergone by the material.

5. Summary

In this study, we determine the value of a plastic strain that a material undergoes using the IIT. This plastic strain value allows determining the springback elastic strain undergone by the material in the location where the indentation test was performed. It is shown that the IIT associated with a method based on the minimization of the difference between the experimental curve and numerical indentation curves of a previously established database leads to a correct determination of the hardening law of a material when it follows the Hollomon law. When a material is plastically deformed, its hardening law differs from a Hollomon hardening law. We show that, in this case, the use of a Voce hardening law is necessary for a correct identification of the hardening law with the inverse analysis optimization. To avoid a problem of uniqueness of solution encountered when trying to identify the three parameters $(\sigma_Y\,;Q;b)$ of the Voce hardening law, it is proposed to use the solution obtained with the Hollomon hardening law as a starting point for the identification procedure by inverse analysis. Results show that by using this method, the indentation technique and an inverse analysis procedure coupled with a FE code provide an accurate identification of the hardening law of a pre-deformed material when the Voce hardening law is implemented in the FE code. This correct identification allows a local determination of the plastic strain and springback elastic strain of the material after a forming process.

Acknowledgment

This work has been partially supported by “la Région Bretagne” and “Rennes métropole”.

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