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NUMERICAL SIMULATION OF THE ROLL LEVELLING OF DP1000 STEEL USING A NONLINEAR COMBINED HARDENING MATERIAL MODEL

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Abstract

The roll levelling is a forming process used to remove the residual stresses and imperfections of metal strips by means of plastic deformations. During the process the metal sheet is subjected to cyclic tension-compression deformations leading to a flat product. The process is especially important to avoid final geometrical errors when coils are cold formed or when thick plates are cut by laser. In the last years, and due to the appearance of high strength materials such as Ultra High Strength Steels, machine design engineers are demanding a reliable tool for the dimensioning of the levelling facilities. In response to this demand, finite element analysis is becoming an important technique able to lead engineers towards facilities optimization through a deeper understanding of the process. Nevertheless, the most commonly used material models, isotropic hardening models, are not able to reproduce the material's Bauschinger effect and the final numerical results are not accurate enough.

In the present paper, the roll levelling simulation of a DP1000 steel is performed using a combined isotropic-kinematic hardening formulation, firstly introduced by Armstrong and Frederick and subsequently modified by Chaboche. For material parameters' identification tension-compression tests and shear-tests have been realized and compared. Finally, the influence of the material model in the numerical results is analyzed by comparing a pure isotropic model and a combined Chaboche hardening model.

Key words: roll levelling, kinematic hardening, high strentgh steels, tension-compression test, shear test

1. INTRODUCTION

The development in the last years of new steel grades with high performances has been motivated by new tendencies in the automotive industry. Reducing the weight of a vehicle is a straightforward strategy to improve fuel economy, but it can potentially create safety problems. For that reason, efforts are concentrated in the development of new steel grades with a competitive strength/weight ratio (van der Wiel, 2012), such as DP-Advanced High Strength Steel (AHSS). However, the development of these materials has led to the apparition of undesirable phenomena during forming process which affect the quality of the final product (Banabic, 2010). Although AHSS shows good mechanical properties in terms of durability, strength, stiffness, good crash energy absorption, etc., there are limiting factors for the application of these steel grades: increased springback, poor formability and high level of residual stresses. Furthermore, forming forces, tool wear and crack appearance increase significantly (Mendiguren, 2012).

Prior to sheet metal manufacturing processes, metal sheets are subjected to hot and cold rolling, which determines thickness and mechanical properties. During this process, sheets adopt flatness defects and residual stresses appear inside the material. High level of residual stresses inside the sheet metal

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at the end of the process can promote the effect of springback, and this could cause the deformation of the sheet during cutting and affect also other forming processes. Thus, flatness tolerances and materials specifications required by manufacturers cannot be usually met by the rolling process itself, and an additional step before forming operation is necessary. The equipment typically employed for this purpose and which is analysed in this paper is the roll levelling process. Roll levelling is a forming process that aims at correcting flatness defects and minimizing residual stresses. For this purpose, sheets are bent in alternate directions, passing from tension to compression, by a certain number of rolls with adjustable overlapping (figure 1). Flattening of the material is achieved by a selective elongation of the shortest material fibres which ensures strain equalization of all fibres across the width and the thickness, thus removing the initial shape defects (Doege et al., 2002).

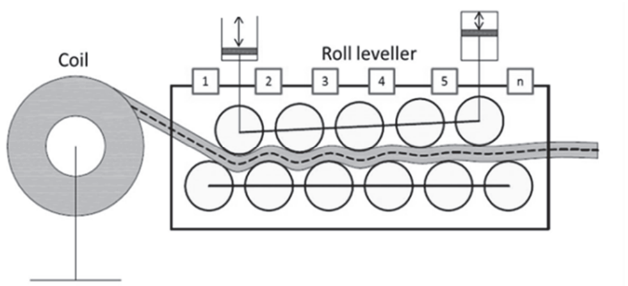

Fig. 1. *Roll leveller diagram.*

Due to the complexity of the process and the search of an optimal roll levelling process, the use of finite element codes which simulate the process has increased significantly in the last years with the aim to reduce cost and optimize the process itself. The finite element method (FEM) is quite successful to simulate metal forming processes, but accuracy depends both on the constitutive laws used and their material parameters identification (Flores et al., 2007). In the last decades, complex hardening models have been developing aiming to properly predict the real material behaviour. For simple applications, isotropic hardening models are usually used assuming proportional expansion of the initial yield surface, acording to the Swift and Voce ones. Kinematic hardening laws provide more sophisticated models, where yield surfaces preserve their shape and size but translate through the stress space. A common rule is the Armstrong-Frederick nonlinear hardening law which considers the Bauschinger effect and the transient behavior. Chaboche improved Armstrong-Frederick kinematic hardening model by creating backstresses through superposition of several kinematic models. There are other advanced models, such as Teodosiu and Hu (1995) or Yoshida and Uemori (2002), ones which improve the fitting of the experimental data but bring about difficulties to identify all the material parameters from experimental stress-strain curves.

Material models with mixed nonlinear isotropic and kinematic hardening laws have received increased attention due to their improved ability to predict the Bauschinger effect and cyclic hardening behaviors of the material (Shi, 2008). One of the most popular of such material models is the Chaboche and Lemaitre model (Lemaitre & Chaboche, 1994), which it is the result of the combination of both Voce isotropic hardening law and Armstrong-Frederick nonlinear hardening law. Different authors argue that the predicted results of numerical simulation are significantly influenced by the choice of the hardening model (Saenz de Argandoña et al., 2014).

Each model has its precise requirements in terms of experimental data and testing needed to identify its parameters. For example, isotropic hardening models are identified on the basis of experimental data obtained from monotonic test methods; however these models overestimate the hardening in reversal loading. The characterization of forming operations such as the roll levelling process, in which tensile-compressive deformations take places, cyclic loading experimental tests are usually used in order to consider kinematic hardening, which is able to describe the Bauschinger effect (Bruschi et al., 2014). Different authors have proposed several reverse loading tests, e.g. tension-compression test, pure bending test, three point bending or shear test (Brunet, 2001; Carbonnière et al., 2009). Tension-compression test is the most simple and straightforward test because stress-strain data are obtained directly during the course of the test and an inverse method is not necessary, as occurs in pure and three point bending test. Nevertheless, the test is difficult to perform, due to the tendency of the specimen to buckle in compression (Eggertsen & Mattiasson, 2011). Shear test provides also tension-compression data directly and it has been used by many authors due to the absaence of necking and the large range of homogeneous strains (Rauch, 1998).

In this paper, two experimental procedures to characterize the hardening behaviour of DP1000 AHSS are presented. In particular, tension-compression and simple shear devices have been developed in order to obtain cyclic stress-strain curves. The modeling of hardening behaviour has been carried out by means of the mixed hardening law developed by Chaboche and Lemaitre with the von Mises yield criteria. The material parameters obtained from the fitting have been implemented in a FE numerical simulation of roll levelling process. An experimental roll leveller prototype have been developed in order to validate the results from simulation with both models.

2. CONSTITUTIVE EQUATIONS

The Chaboche and Lemaitre hardening model (Lemaitre & Chaboche, 1994) has been combined with the von Mises yield criteria, since it is recommended to use for cyclic plasticity analyses and it is widely distributed in commercial FE-codes. The von Mises yield criteria can be expressed for the uniaxial loading case:

$$\phi(\sigma, X, \sigma_y) = |\sigma - X| - \sigma_y \, , \qquad (1)$$

Where σ denotes the stress tensor, X is the backstress tensor and σ_y is the initial yield stress. It is a mixed isotropic-kinematic hardening law which describes the movement of the yield surface corresponding to the nonlinear kinematic hardening by means of the evolution of the backstress, and the change in the size of the yield surface, which is introduced by means of the initial value of the yield stress σ_y and the isotropic variable R. In the proposed model, the evolution of isotropic hardening is defined in function of the accumulated plastic strain $d\overline{\varepsilon^p}$ by the following law:

$$dR = b \cdot (Q - R) \cdot d\overline{\varepsilon^p} \qquad (2)$$

where Q and b are material parameters and the accumulated plastic strain. The kinematic part was proposed by Chaboche and his co-workers. This model is based on a decomposition of the non-linear kinematic hardening rule proposed by Armstrong and Frederik (1966):

$$dX_i = {}^2/_3 \cdot C_i \cdot d\varepsilon^p - \gamma_i . X_i \cdot d\overline{\varepsilon^p} \, , \qquad (3)$$

Chaboche decomposed a stable hysteresis curve in several parts, and it was observed that increasing the material parameters of the hardening rule, a more accurate model was obtained. The use of three components has been recommended by several authors (Bari & Hassan, 2000; Mahmoudi et al., 2011).

3. EXPERIMENTAL PROCEDURE

3.1. Materials

Dual phase steel DP1000 consisting of a ferritic matrix containing a hard martensitic second phase in the form of islands has been used in this study. This material is often used in the automotive industry, in particular for the roof rails. It is supplied in 1.0 mm thickness.

3.2. Tensile test

To determine material properties, a uniaxial tensile test has been performed at 0º to RD. The specimens were cut following ASTM E 8M-04 standard. The experiments have been carried out at 0,05 mm/s on a Universal 5 Tn Zwick/Roell machine. The initial yield stress YS, the ultimate tensile strength UTS, the Young modulus E and the elongation are given in table 1.

*Table **1**. Material parameters of DP1000.*

YS 0.2% (MPa)	UTS (MPa)	*E* (GPa)	Elongation (%)
922.19	1055.75	196.80	8.74

3.3. Tension-compression test

The test provides suitable stress-strain curves under small strain ranges, however the maximum plastic strain achieved with this method is limited. Another inconvenience of this test is the buckling for thin sheet in compression loading. For this reason a special tool to avoid the buckling has been developed and its description is presented below. The specimens were cut from sheet for the 0º rolling direction. The specimens are smooth rectangular with the same cross section as the specimen used in the tensile test and a calibrated length of 22.5 mm. The geometry of the specimens has been specially designed for this study with the aim to use them in a tool preventing buckling. Figure 2a shows the experimental test equipment used.

3.4. Simple shear test

A simple shear sample similar to the proposed by Miyauchi (1984) has been developed with a two gauged areas of 1.5x35.2 mm^2 (figure 2b). The device developed allows for a reverse simple shear test and can be implemented in any tensile test machine.

Monotonic test has been performed at 0º to RD in the same way that the tension-compression test. Sample surface has been marked with small black dots over a white plane surface. The optical measurement system Aramis® from GOM has been chosen to measure the deformation of the specimen. Surface strains are calculated from the deformation of the pattern relative to a reference point.

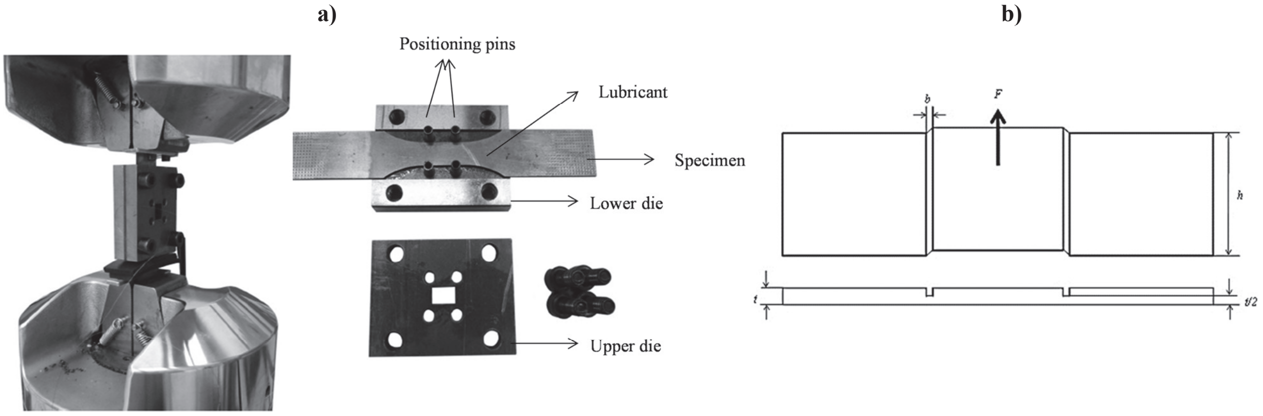
a)
b)

Fig. 2. Experimental equipment to avoid buckling during tension-compression test (a), shear specimen (b).

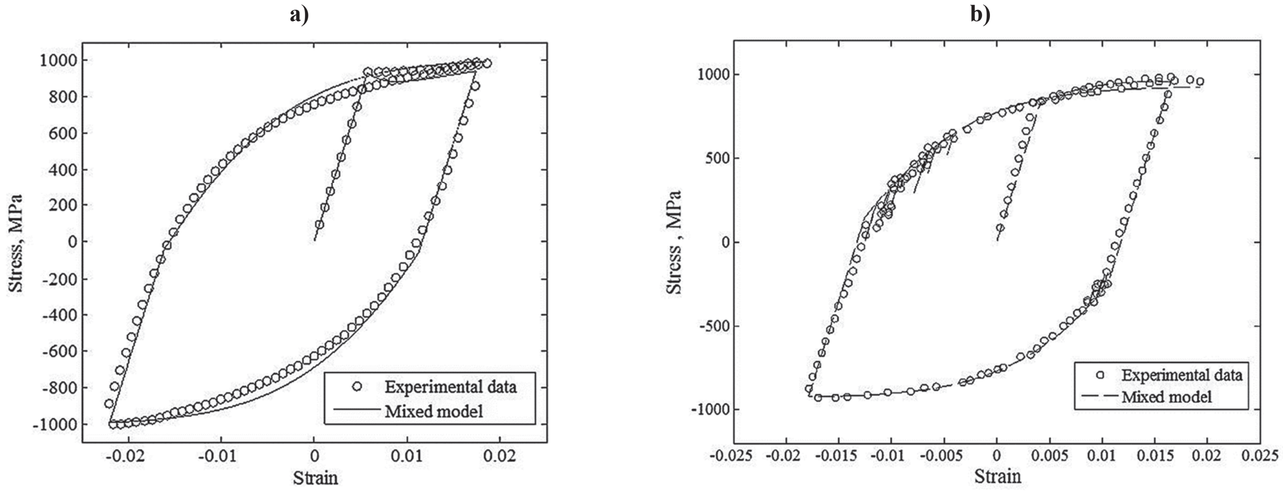
a)
b)

Fig. 3. Fitting of mixed hardening model to: tension-compression test data (a) and simple shear test data (b).

4. MATERIAL PARAMETER IDENTIFICATION

Identification of hardening parameters has been carried out by means of the Nelder and Mead (1965) minimization method, which is a nongradient optimization method. The program was implemented as a function of Matlab®, so that the objective function was defined to minimize the difference between the predicted stress values from the model and the experimental data:

$$f = Min\frac{1}{n}\sum_{i=1}^{n} abs\left[\frac{(\sigma_i^{exp}-\sigma_i^{model})\cdot 100}{\sigma_i^{exp}}\right] \quad (6)$$

where n is the number of experimental data, σ_i^{exp} is the stress obtained in experimental test and σ_i^{model} is the stress predicted by the proposed model. The identification method consists of the search of the optimal parameters which minimize the objective function (6). In particular, the model has 4 hardening material parameters, two corresponding to the isotropic equation (Q, b) and other two corresponding to the kinematic equation (C, γ).

5. RESULTS AND DISCUSSION

The optimization has been carried out for the experimental data obtained from the tension-compression test and from shear test. In both cases, the parameters obtained from resolution of the model equations by using know states of backstress, R and increment of plastic strain from experimental data have been used as initial guesses. The initial parameters obtained are presented in table 2.

Table 2. *Initial parameters for the optimization process.*

Q_0 (MPa)	b_0	C_0 (MPa)	γ_0
100.00	-51.74	55000.00	177.95

5.1. Parameter identification with tension-compression and simple shear test

Fitting of the mixed hardening model to the experimental data from tension-compression test and simple shear test are presented in figure 3a and 3b, respectively. Both figures show an excellent correlation between experimental and simulated data. A good prediction of the Bauschinger effect, cyclic softening and transient behavior are obtained. Material parameters obtained from both fittings are shown in table 3.

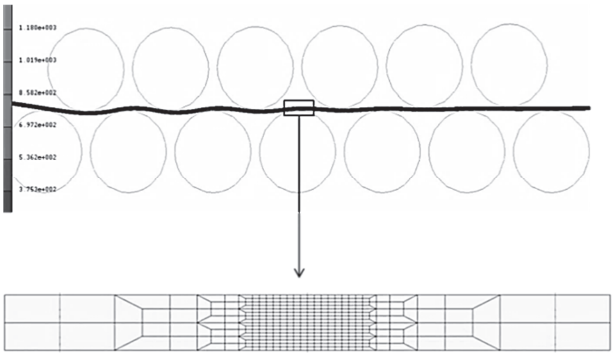

Fig. 4. *2D finite element model geometry and sheet meshing.*

Table 3. *Material parameters of Chaboche and Lemaitre model obtained from tension-compression test.*

Test	Q (MPa)	b	C (MPa)	γ
Tension-compression	-460.02	250.78	80502.77	150.70
Simple shear	-299.86	113.00	69525.85	172.74

6. NUMERICAL SIMULATION AND VALIDATION OF THE MODEL IN A ROLL LEVELLING PROTOTYPE

6.1. Numerical simulation

2D numerical model has been developed in MSC Marc® software. The model consists of two rows of work introducing a proper deformation to the sheet. The work rolls rotate in order to push the sheet through them as it is shown in figure 4. The sheet has been discretized using a non-uniform mesh of elements with four integration points. The friction coefficient of 0.2 was taken.

The material parameters of Chaboche and Lemaitre model obtained in the previous section from tension-compression test and shear test were evaluated by simulating the roll levelling process using both set of parameters.

6.2. Experimental equipment

A 13-rolls leveller prototype was designed in order to validate numerical simulations. The prototype has several sensors to capture signals of different process variables: loading cells to measure the reaction force supported by the machine, torque sensor

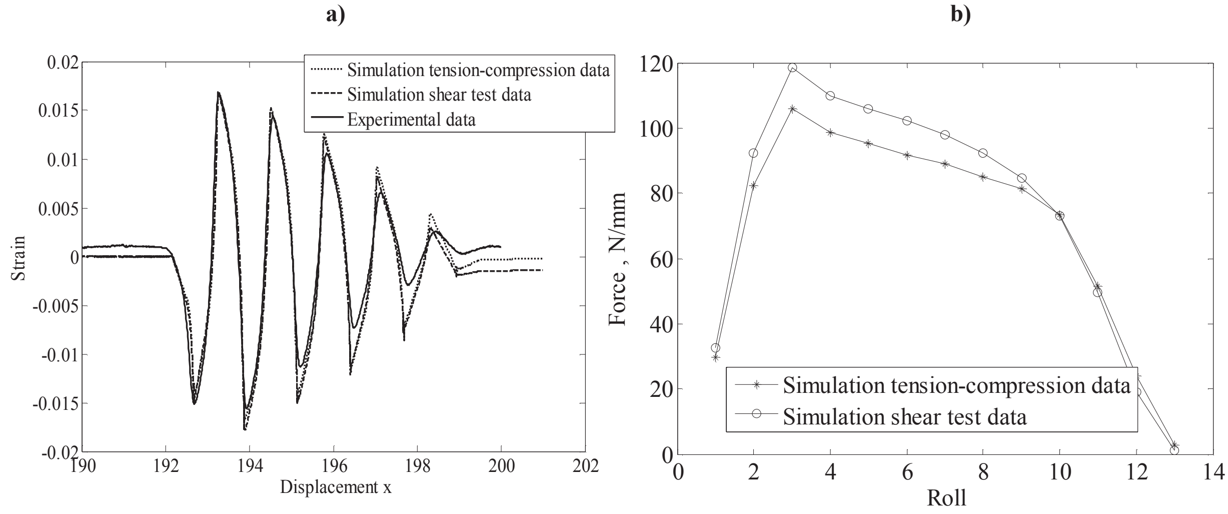

Fig. 5. *Strain path in the surface of the sheet during the process (a), simulation result of force per roll (b).*

in the most critical roll, power consumption device and instrumented sheet with gauge strain at the surface in order to check the deformation of the sheet during the process.

6.3. Validation of numerical simulation of roll levelling with tension-compression and simple shear parameters

The strain path of a point at the surface of the sheet during the levelling process has been determined with both material models. In figure 5a the comparison of the numerical strain path with the experimental data is presented. A negligible difference between both models is perceived. Deviation between the experimental data and numerical results can be appreciated in the last rolls. This difference can be caused by the displacement of rolls during the test due to the reaction forces which the sheet applies in the work rolls. In terms of maximum plastic rate achieved during the process (percentage of thickness which achieves the platic range), only 1% difference was found between the simulation and the experimental data (74% and 73%, respectively).

Simulation using the parameters from tension-compression test has provided slighty lower values of force per roll than shear test simulation (figure 5b). The total force of the machine in the simulation has been calculated as the sum of the reaction forces of the top rolls and has been compared with the total force measured in the prototype. The values are presented in table 4.

Table 4. *Comparison between experimental and simulation values of force and strain.*

Variable	Experimental	Simulation with tension-compression test parameters	Simulation with simple shear test parameters
Total Force (kg)	9000	9291	9973
Maximum plastic rate (%)	73.2	73.8	74.2

7. CONCLUSIONS

In order to develop an accurate methodology to develop hardening models for Advanced AHSS, such as DP1000, two methodologies of material characterization have been checked.

- Tension-compression and simple shear devices have proven to be a fast and easy test to recover cyclic reverse loading data, and an inverse method is not necessary.
- Chaboche and Lemaitre hardening model has been selected due to its ability to predict the Baushchinger effect and because it is implemented in most of finite element codes.
- The fitting to the experimental data from both characterization test has given different material parameters. Bauschinger effect and transient behaviour has been predicted in both cases.
- Numerical simulation of roll leveling process has been compared with experimental data obtained from a roll levelling prototype. The strain paths along the process obtained from simulation are quite similar to the experimental strain path (1% difference). Total force measured in tension-compression and simple shear simulation were 3.2% and 10.8% respectively higher than the experimental data.

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SYMULACJA NUMERYCZNA WALCOWANIA POZIOMUJĄCEGO STALI DP100 Z ZASTOSOWANIEM NIELINIOWEGO MODELU UMOCNIENIA MATERIAŁU

Streszczenie

Walcowanie prostujące jest procesem odkształcania stosowanym do usuwania naprężeń szczątkowych i niedoskonałości pasma po walcowaniu, wykorzystującym odkształcenia plastyczne. Podczas procesu blacha jest poddawana cyklicznym odkształceniom rozciągająco-ściskającym, prowadzącym do otrzymania produktu płaskiego. Proces jest szczególnie istotny, gdy w ostatnim etapie produkcji blacha jest zwijana lub, jak w przypadku blach grubych, stosowane jest cięcie laserowe, gdyż pozwala uniknąć błędów kształtu. W ciągu ostatnich lat, ze względu na coraz szersze wykorzystywanie materiałów o wysokich własnościach wytrzymałościowych, takich jak stale typu UHSS, przed konstruktorami maszyn pojawiają się zadania projektowania niezawodnych i precyzyjnych narzędzi do walcowania prostującego. Numeryczna analiza procesu, wykorzystująca modelowanie metodą elementów skończonych, stała się ważną techniką, pozwalającą inżynierom na optymalizację tego procesu poprzez jego lepsze, głębsze zrozumienie. Niemniej klasyczne modele umocnienia materiału, modele izotropowe, nie oddają efektu Bauschingera obserwowanego w trakcie walcowania prostującego, przez co ilościowe wyniki obliczeń nie są wystarczająco dokładne.

W niniejszej pracy, przeprowadzono symulację procesu walcowania prostującego dla stali DP100 wykorzystując izotropowy, kinematyczny model umocnienia materiału, wprowadzony po raz pierwszy przez Armstronga i Fredericka, a następnie zmodyfikowany przez Chaboche'a. Identyfikację parametrów modelu przeprowadzono na podstawie wyników testów rozciągania i ściskania oraz prób ścinania. Ponadto w pracy zbadano wpływ modelu materiału w obliczeniach numerycznych porównując wyniki otrzymane dla czystego modelu izotropowego i modelu Chaboche'a umocnienia materiału.

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