Roll levelling numerical simulation using a nonlinear mixed hardening material model

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Abstract. 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 fibers are 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. Aiming to study the influence of the material model in roll levelling simulation, a mixed isotropic-kinematic hardening formulation, firstly introduced by Armstrong and Frederick and subsequently modified by Chaboche, has been used in the present work. A MS1200 high strength steels and a DC04 mild steel are analyzed. Both materials are characterized, using uniaxial tensile tests and uniaxial cyclic tension-compression tests. Finally the influence of the material model in the numerical results is analyzed by comparing a pure isotropic model and a mixed Chaboche hardening model.

Keywords: Roll levelling, kinematic hardening, ultra high strength steels, tension/compression test, parameter identification

1. INTRODUCTION

With the introduction of new high performance steel grades, efficient and sophisticated forming techniques of thin sheets are required. Specifically, the automotive industry is becoming more and more competitive in this area. In this context, High-Strength-Steels (HSS) and Ultra-High-Strength-Steel (UHSS) offer great possibilities for weight and fuel consumption reduction and safety improvement.

Roll levelling is a forming process that aims at correcting flatness defects and minimizing residual stresses where sheets are bent in alternate directions by a certain number of rolls. During this process, materials are subjected to elasto-plastic deformations within the levelling machines leading to complex behaviours of the material. As an initial step in order to improve the control of the process, several attempts have been carried out in order to better understand the behaviour of the material. This way, Doege et al. [1] carried out an analysis of the levelling process based on a one-dimensional analytical model. This model needs a very short calculation time and uses bending theory to find the optimal set up for the rolls. Dratz et al [2] developed three different models (a finite element approach, an analytical approach and a semi-analytical approach) to determine the loading modes experienced by the material in roll levelling operations. Other authors have proposed finite element models to simulate the sheet behaviour, taking into account cyclic elasto-plasticity and the Bauschinger effect in their own code. Analytical models have the advantage that they need a shorter computational time than EF method. However they require several assumptions in the model which restrict the accuracy of the results significantly.

From the material point of view, different yield functions and hardening models [3] can be combined to achieve optimal numerical models able to consider the phenomena that occur during cyclic loading, such as the Bauschinger effect, the transient behaviour, the permanent softening and the work hardening stagnation. These effects are defined by the hardening law. In all the processes where cyclic plasticity performance occurs, an isotropic-kinematic hardening model seems to be the most appropriate. A pure isotropic model provides poorly accurate results, but combined with a kinematic model significant improvements can be achieved. The complexity of the model depends on the number of material parameters which have to be identified.

At the present research a von Mises yield criterion with the Chaboche nonlinear mixed (isotropic + kinematic) hardening law with four parameters is chosen to model the material behaviour. The model is obtained from the tension/compression test. This test is the simplest one because an inverse method in order to calculate the parameters is not necessary. However, there is a tendency of the strip to buckle under compression load during the test. At the present research, an experimental equipment for cyclic testing has been successfully developed to avoid the buckling effect.

This way, the tension/compression tests are directly carried out to identify the material parameters by means of an optimization technique. Finally, numerical results of a levelling process are compared when using a mixed material model and a pure isotropic model.

2. MIXED HARDENING MODEL

The selected model is a mixed isotropic-kinematic hardening formulation introduced by Chaboche and Lemaitre [4, 5]. A proper hardening law must describes the movement of the yield surface corresponding to the kinematic hardening and the change in the size of the yield surface corresponding to the isotropic hardening.

In this unidimensional model with mixed hardening the yield function leads

$$\Phi(\sigma, X, \sigma_y) = |\sigma - X| - \sigma_y, \tag{1}$$

where Φ, represents the yield function, while X, is the backstress tensor characteristic of the kinematic hardening and σ_y, is the size of the yield surface defined by the isotropic hardening. The Chaboche's mixed hardening model is implemented in this work; the kinematic hardening is introduced by using the Armstrong-Frederick formula [6],

$$\mathrm{d}X = C \cdot \mathrm{d}\bar{\varepsilon}^{\mathrm{p}} - \alpha \cdot X \cdot \mathrm{d}\bar{\varepsilon}^{\mathrm{p}}, \quad (2)$$

where C and α, are material constants and $\mathrm{d}\bar{\varepsilon}^{\mathrm{p}}$,is the increment of accumulated axial plastic strain $\bar{\varepsilon}^{\mathrm{p}}$.

The yield surface size is represented by

$$\sigma_{\mathrm{y}} = \sigma_{\mathrm{y0}} + R, \quad (3)$$

where σ_{y0}, is the initial yield stress and R, represents the isotropic hardening written as

$$\mathrm{d}R = b(Q - R)\mathrm{d}\bar{\varepsilon}^{\mathrm{p}}, \quad (4)$$

where Q , and b , are material parameters.

2.1 Investigated materials

In this study two different steels have been investigated with the aim of analysing their modelization in levelling processes: a MS1200 high strength steels and a DC04 mild steel. Figure 1 shows the specimen geometry used for mechanically characterising both materials. The specimens are smooth rectangular with a cross section 1.5 mm thick and 12.5 mm width, and a calibrated length of 22.5 mm. The specimens have been cut in a wire electrical discharge machine in order to minimize the influence of the cutting on the microstructure and behaviour of the specimens. Table 1 shows the mechanical properties of the investigated materials.

2.2 Tension/compression test.

A servo-hydraulic MTS 810 Material Test System has been used for the tension/compression tests. Data has been acquired through an axial load cell and strains have been measured with 350Ω strain gages which were located in the middle of the specimen.

In the experiments the specimen has been subjected to tension/compression cycles, controlling the machine by displacement. A displacement of 1070 µm in tension and -1070 µm in compression has been applied.

Figure 2 shows the experimental test equipment used to avoid buckling [7]. The specimen has been clamped between the two holders leaving a 0,1mm gap and has been lubricated by Rhenus Fe 1300 lubricant in order to eliminate the influence of friction forces during the test. One of the holders has a hole where the gage strain is placed.

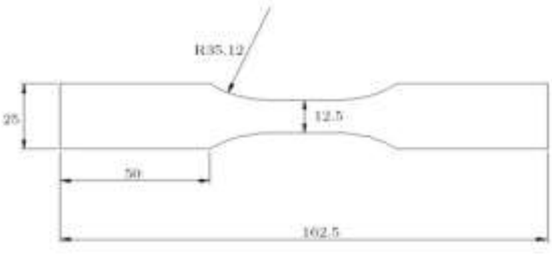

Figure 1. Rectangular test specimen details

Table 1. Mechanical properties of investigated materials

Material	*Yield stress* σ_y	*Maximum stress* σ_r	*Elongation A*
MS1200	1100 MPa	1380 MPa	3%
DC04	193MPa	420 MPa	35%

2.3 Parameter identification

The identification of the hardening parameters of the Chaboche's mixed model has been carried out by means of the Nelder and Mead minimization method [8, 9], which is implemented in the *fminsearch* function of Matlab®. The objective function $f(x)$ is defined as:

$$f(x) = \sum_{i}^{imax} (F(di) - Fi)^2 \quad (5)$$

where: x denotes the model parameters, i is the index of summation, $imax$ is the total number of experiments, $F(di)$ and Fi are the force values of the FEM model and the ith experimental force for the ith experimental displacement di, repectively.

3. FINITE ELEMENT MODEL (FEM)

The numerical model has been created by Marc® software. Two simulations per material have been carried out with the same set up in order to analyse the roll levelling process when a pure isotropic and a mixed hardening model were defined. The levelling configuration was composed of 13 rolls with an initial penetration of -1.9 mm and a final penetration of 0.5 mm. A friction coefficient of 0.05 has been established for the process. The sheet has been discretized using Quad4 elements and the meshing employed has been described with a non-uniform distribution along the sheet. A finer mesh with 16 elements in height has been used in the central area of the sheet to provide more accurate and stabilized results (see figure 3b), meanwhile a coarser mesh with 4 elements in height has been used in the rest of the sheet to reduce the computational time.

The model has been created by assuming that the sheet was static and the rolls move and rotate towards the sheet. The main purpose of this modelization has been to decrease the computational time of the simulations. Figure 3 shows the 2D finite element model developed and its geometry specifications are detailed in table 2.

Table 2. Geometry of FEM model for roll levelling.

Nº roll	Sheet thickness	Roll diameter	Distance between roll	Input penetration	Output penetration
13	2 mm	45 mm	50 mm	-0.5mm	1.9 mm

4. RESULTS AND DISCUSSION

In this section the results achieved in the material modelization using the different models and the way that the material modelization affects the simulation results for the levelling process are shown.

Figure 2. Experimental set-up used in tension/compression cyclic test: **a** test equipment, **b** tool for avoids buckling.

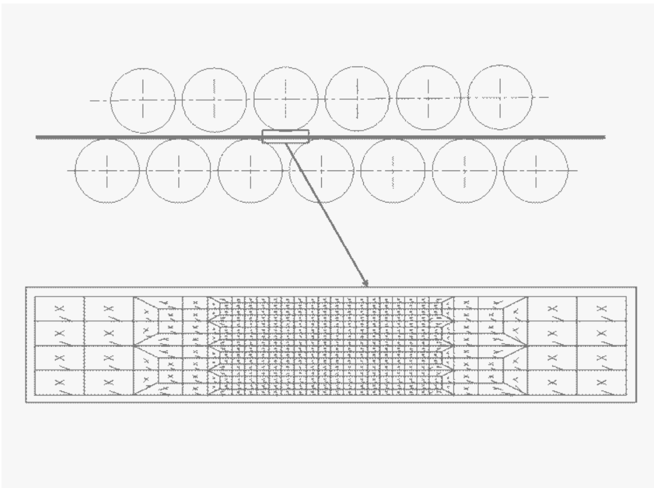

Figure 3. **a)**2D finite element model diagram **b)**mesh size

4.1 Material modelling results

The parameters for Chaboche's mixed hardening model have been fitted to the curves achieved in tension/compression tests by means of an optimization method for both materials. The parameter values obtained are exposed in table 3.

Table 3. Optimum parameter combination obtained in tension/compression test for each material (Chaboche's mixed hardening model).

Material	*Q* (Pa)	*b*	*C* (Pa)	*α*
MS1200	$1.475\cdot10^{8}$	$7.171\cdot10^{-14}$	$2.141\cdot10^{10}$	18.93
DC04	$4.1\cdot10^{6}$	2.7751	$9.675\cdot10^{9}$	223.323

The pure isotropic hardening modelization of the materials has been based on the initial loading of the same curves. The curve is represented by experimental values of yield stress and plastic strain until 2% of strain. After this strain, the curve is extended with more values calculated by a hardening law in the way:

$$\sigma_y = K \cdot (\varepsilon_p)^n \quad (6)$$

The curve is fitted and the parameter values obtained are exposed in table 4.

Table 4. Optimum parameter combination obtained for the modelization of the first loading phase for each material

Material	*K*	*n*
MS1200	7.3186	0.0256
DC04	5.8497	0.1024

Where *K* is the strength index and *n* is the strain hardening exponent.

4.2 Levelling process numerical results

During the levelling process the stress and strain in a node at the surface of the sheet have been studied. Figure 4 shows the stress-strain path of the node through the process. Depending on the hardening law which has been used, two different behaviours are observed in the node.

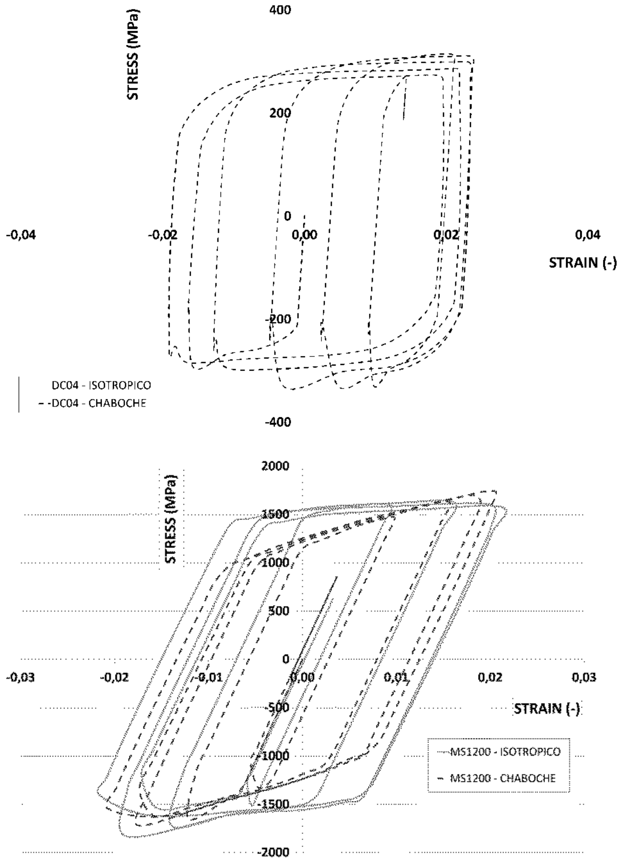

Figure 4. Stress-strain path of a surface node through the process depending on the material model **a)** DC04 **b)** MS1200

From the process point of view, the different behaviors of the materials give as a result that the forces applied by the rolls differ as well. Figure 5 shows the reaction forces at the different rolls that compose the levelling process.

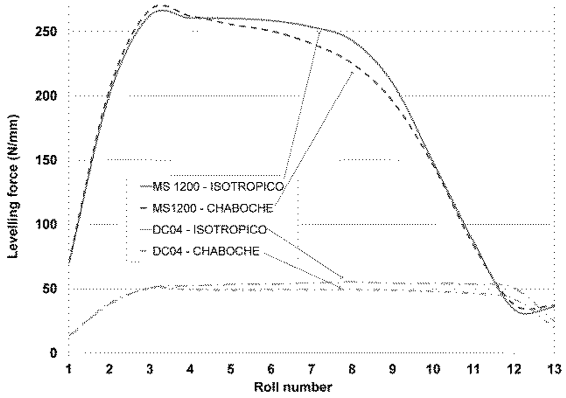

Figure 5. Reaction forces

The levelling process purpose is to minimize the residual stresses at the sheet. This means that the sheet must show an uniform and low level of stresses along its thickness at the end of the process. This has been evaluated by analyzing the stress of the sheet along its thickness after the last roll, as shown in figure 6.

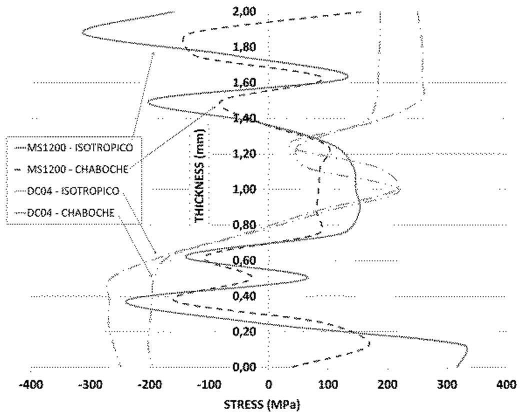

Figure 6. Residual Stresses at the end of levelling process

4.3. Discussion

Table 3 shows that the MS1200 steel has an almost pure kinematic hardening because its isotropic hardening is practically negligible. On the other hand, the DC04 has a combination of both, isotropic and kinematic hardening.

Figure 4 shows the stress-strain path when modelling the materials with an isotropic and a mixed hardening model. There are bigger differences in the case of DC04 steel than in the case of MS1200 steel. First conclusion from this figure 4 is that both stress path and strain path depend on the material model. In terms of strain, the dynamic of the process affects the strain path. Therefore, each material behaves in a different way to the same rolls configuration, adopting different deformation states. As concerns about stress, figure 4 shows that the DC04 mixed hardening model shows both isotropic and kinematic hardening components because its yield surface expands and moves during the process. In the case of the MS1200, it is observed that the isotropic component of the hardening is almost negligible (as observed also in table 3) because its yield surface does not expand at all during the process.

The differences shown in the material behaviour affect the process levelling variables. This is the case of the reaction force at the rolls that are directly influenced by the material model. Comparing both materials, the difference is greater in the case of DC04 steel, due to its greater hardening exponent.

When analysing the residual stresses, figure 6 shows that different hardening models predict different stress distributions what in fact affects the final quality of the levelling process. The isotropic hardening model is more pessimists for both materials because it predicts a bigger level of stresses in the material at the end of the process.

5. CONCLUSIONS

Tension/compression test is a fast and easy test to recover mixed hardening material data. At the present research, both isotropic and mixed hardening models have been obtained from this method.

Depending on the hardening model different stresses and strains are predicted in the material due to the process dynamic. Therefore the identification of hardening models able to reproduce the material behaviour in levelling processes is very important for achieving accurate results.

When comparing both materials, MS1200 high strength steel shows an almost pure kinematic hardening meanwhile the DC04 mild steel shows a mixed hardening.

In terms of process parameters, smaller reaction force differences have been observed for the MS1200 high strength steel when comparing both hardening models. This is due to the fact that MS1200 steel presents a smaller hardening exponent than the DC04 mild steel.

And finally the pure isotropic material model is more pessimists in terms of residual stresses for both materials.

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