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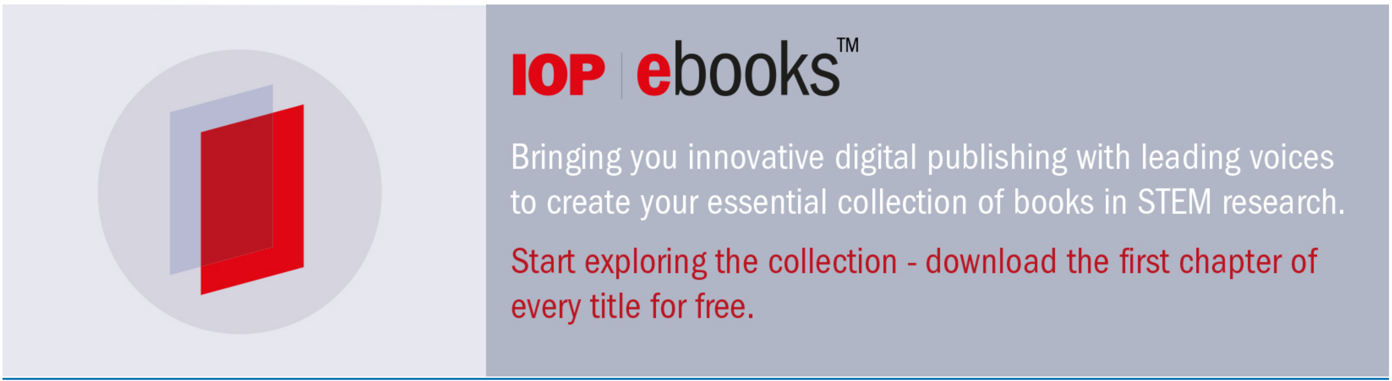

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Numerical simulation of the roll levelling of third generation fortiform 1050 steel using a nonlinear combined hardening material model

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Abstract. The roll levelling is a flattening 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 reliable tools for the dimensioning of the levelling facilities. Like in other metal forming fields, finite element analysis seems to be the most widely used solution to understand the occurring phenomena and to calculate the processing loads. In this paper, the roll levelling process of the third generation Fortiform 1050 steel is numerically analysed. The process has been studied using the MSC MARC software and two different material laws. A pure isotropic hardening law has been used and set as the baseline study. In the second part, tension-compression tests have been carried out to analyse the cyclic behaviour of the steel. With the obtained data, a new material model using a combined isotropic-kinematic hardening formulation has been fitted. Finally, the influence of the material model in the numerical results has been analysed by comparing a pure isotropic model and the later combined mixed hardening model.

1. Introduction

The development 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 has been focused to launch new steel families with a competitive strength/weight ratio. The best example is the development and extensive use of Advanced High Strength Steels (AHSS) by the automotive industry for the body in white construction [1].

However, it is well known that the formability of steels decreases dynamically with increasing strength. This is obviously valid for the newly developed high-strength steels as well [2]. Besides the significant decrease in formability, the increased post-forming springback is one of the biggest technological problems when defining and developing new high strength sheet metal components. Current industrial problems when using these materials are premature cracks and excessive set-up times needed for springback compensation.

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Aiming to reach higher yield and ultimate tensile strengths together with improved formability ratios, principal steel makers developed the TRansformation Induced Plasticity (TRIP) steels and Twinning-Induced Plasticity (TWIP) steels. Production costs of these new steels are high and automotive industry has adopted superior Dual Phase steels as the first option for their steel-based designs.

Nevertheless, a property gap exists between the currently available AHSS grades of the first and second generations and defines a property band for future "Third Generation" AHSS. Current research is hence focused on filling this property window using modified or novel processing routes where special attention should naturally also be given to industrial feasibility and cost effectiveness are based on the use of high amount residual austenite phase fractions [3-5]. The lightweighting potential of the new commercial third generation steels is said to be around 20% in comparison to already used Dual Phase steels. For example, the Dual Phase 780 steel has a yield strength of 480 MPa and an ultimate strength of 830 MPa. Having the same formability and comparable forming limit curve, the Fortiform 1050 steel, the material studied in this paper, has a yield strength of 760 MPa and an ultimate strength of 1100 MPa.

The equipment typically employed to flatten coils and eliminate existing defects coming from the rolling mill is the roll levelling process. 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 fibers which ensures strain equalization of all fibers across the width and the thickness, thus removing the initial shape defects [6].

In this paper, the third generation high strength steels behavior during the roll levelling process is numerically analyzed by finite element modelling using two different material hardening models. The final aim of the study is to analyze the effect this input has on the numerical outputs in order to develop a reliable model and tool for the dimensioning of the levelling facilities to be used by the machine design engineers.

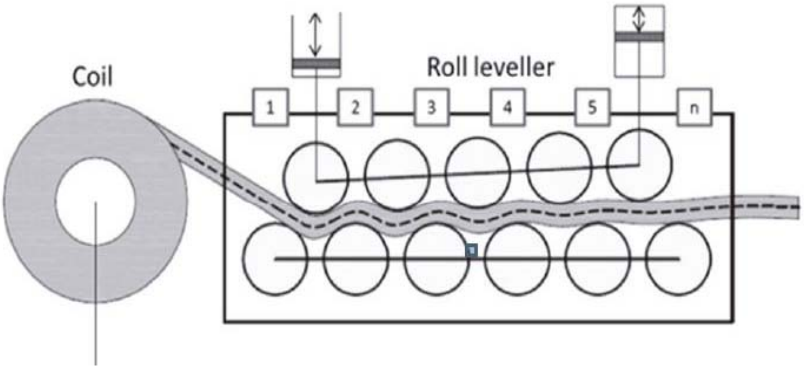

Figure 1: Roll levelling machine**.**

2. Hardening models and Constitutive equations

Due to its simplicity, isotropic hardening models are usually used in finite element modelling assuming a proportional expansion of the initial yield surface. On the other hand, when using kinematic hardening laws, 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 [7] or Yoshida and Uemori [8], that improve the accuracy of the experimental data fitting but are more complex in terms of material parameters identification. 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 [9]. One of the most popular of such material models is the Chaboche and Lemaitre model [10], being the result of the combination of both Voce isotropic hardening law and Armstrong-Frederick nonlinear hardening law.

Cyclic loading experimental tests are usually used in order to consider kinematic hardening [11]. Different authors have proposed several reverse loading tests, e.g. tension-compression test, pure bending test, three point bending or shear test [12-13]. 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 [14-15]. 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 [16].

Chaboche and Lemaitre hardening model has been used together with theVon Mises yield criteria in this paper, 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:

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

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:

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

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 descomposition of the non-linear kinematic hardening rule proposed by Armstrong and Frederik (1966):

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

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.

3. Fortiform 1050 material characterization

The studied material is an electrolytically galvanized third generation Fortiform 1050 steel, from Arcelor Mittal, having a thickness of 1.2 mm. Chemical composition and mechanical properties are shown in table 1.

Table 1. Chemical composition and mechanical properties of Fortiform 1050.

C	Mn	P	S	Si	Al	N	YS (MPa)	UTS (MPa)	A%
0.2069%	2.1755%	0.0107%	0.0005%	1.4521%	0.0366%	0.0051%	775	1235	10

Besides the mechanical properties, the Lankford or anisotropy coefficients of the material have also been obtained following the ASTM E 517-00 standard and using GOM ARAMIS digital image correlation technique. The Lankford coefficients at different directions and the monotonic hardening curve are shown in figure 2 (left side). Based on these results, the monotonic behaviour of the material has been modelled using a combined Swift–Hockett/Sherby hardening model (see equation 4). The parameters of the model are as follows: ε_0=0.00312, m=0.14, C=1725, σ_i=766.8, σ_{sat}=1435, a=5.91, p=0.657, α=0.25.

$$\sigma = (1 - \alpha)\left\{C\left(\varepsilon_{pl} + \varepsilon_0\right)^m\right\} + \alpha\left\{\sigma_{sat} - (\sigma_{sat} - \sigma_i)e^{-a\varepsilon_{pl}^{p}}\right\} \tag{4}$$

Tensile-compression tests have been carried out in order to identify the kinematic behavior of the material. A servo hydraulic MTS 810 Material Test System has been used for the experiments. Force data has been acquired through an axial load cell and strain data has been measured with small strain gauges to obtain continuous measurement. A maximum strain of +2% in tension and -2% in compression has been achieved during the tests. The experimental results and the experimental test equipment used to avoid specimen buckling are shown in figure 2 (right side).

Identification of hardening parameters has been carried out by means of the Nelder and Mead minimization method [17], which is a gradient-based optimization method. The program has been implemented as a function of Matlab®, so that the objective function has been defined to minimize the difference between the predicted stress values by the model and the experimental data:

$$f = Min\frac{1}{n}\sum_{i=1}^{n} abs\left[\frac{(\sigma_i^{exp}-\sigma_i^{model})\cdot 100}{\sigma_i^{exp}}\right] \tag{5}$$

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 on the search of the optimal parameters which minimize the objective function (eq. 5). 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). Initial guess values for the optimization and fitting of the parameters have been identified from the resolution of the model equations and by using known states of backstress. The final material model parameters are shown in table 2 and experimental and fitted cyclic hardening curves are shown in figure 2 (left side).

Table 2. Parameters of Chaboche and Lemaitre model obtained from tension-compression test.

Q (MPa)	b	C (MPa)	ɣ
-17.62	3.715	13539.38	81.576

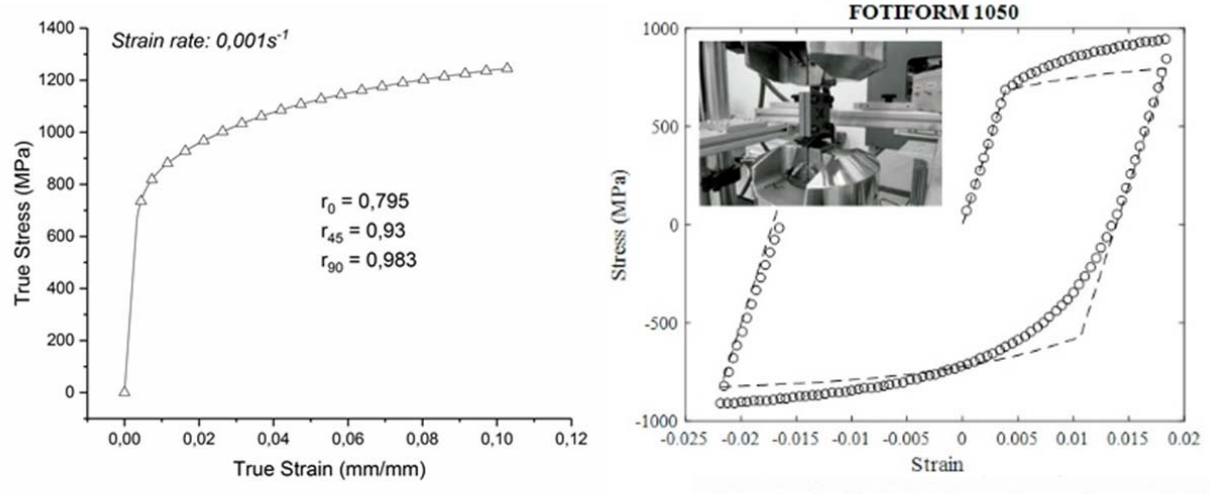

Figure 2: Monotonic tensile test and Lankford coefficients (left) and tensile-compression test (right) for Fortiform 1050 material.

4. Numerical simulation results of roll levelling

The 2D plane strain numerical model has been developed in MSC Marc® software. The model consists on two rows of work rolls placed at a specific value of setting which provides a theoretical thickness plastification of 75%. The rolls rotate in order to push the sheet through the exit. The sheet has been discretized using elements with four integration points and a fine mesh zone has been used to obtain the numerical results. A friction coefficient of 0.14 was established following the works performed by Mondragon University for friction coefficient calculation [18]. In order to evaluate the numerical results, the strain path of a node located at the upper surface of the sheet has been followed with both material models, the isotropic and the mixed hardening one. In figure 4 the strain paths for both models are shown where 11 peaks created by the 13 levelling rolls are clearly identified.

Additionally, and in order to evaluate the influence the material model has on the main output variables used for machine dimensioning, the rolls force and rolls torque have been obtained from numerical master roll nodes. Numerical results for both variables and both material models are shown in figure 5 and figure 6.

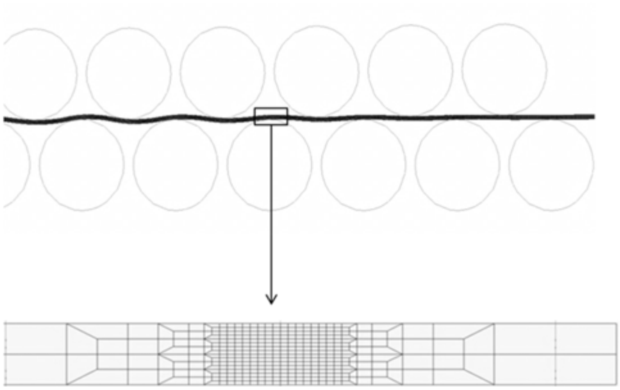

Figure 3: 2D finite element model and mesh detail.

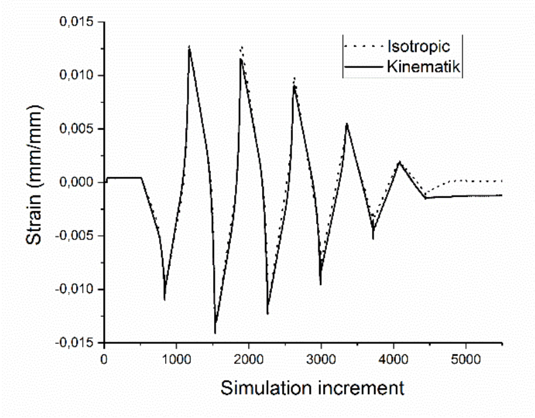

Figure 4: Strain path of upper side.

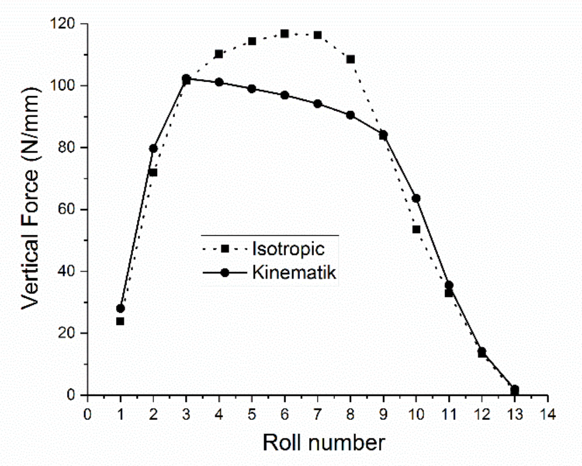

Figure 5: Reaction force for different rolls.

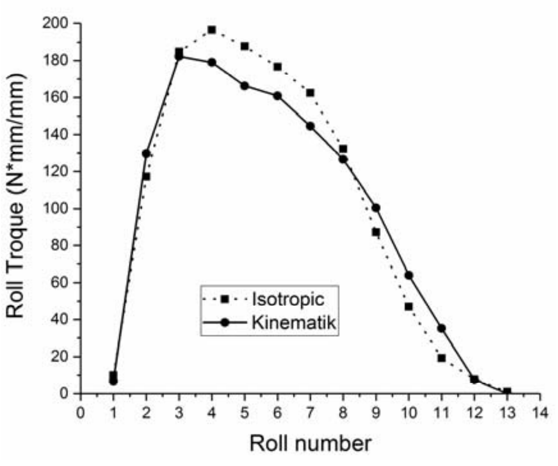

Figure 6: Torque for different rolls.

5. Conclusions

Slightly bigger strain levels are obtained for the isotropic hardening model in comparison to the mixed hardening one. This difference is especially noticeable for the second and third upper tensile strain peaks. This evidence reveals the numerical coil shape is affected by the hardening model of the material. Bigger the hardening, obtained when using the isotropic hardening model, less is the roll hugging. In consequence, contact between roll and coil does not occur in the roll center. The maximum peak is shifted to the right side, a smaller bending radius is created than the one caused by the work roll and a bigger strain level is achieved.

The maximum thickness plastification level obtained in both cases is similar, 76.9% for the mixed hardening model and 76.6% for the isotropic case. Although the strain levels are bigger in the isotropic hardening model, the highest plastification of the sheet is achieved in the fourth roll (third peak of figure 4) being very similar or both models. This results is significant since this measure is widely used in industry to indicate a good quality of levelling.

Regarding the roll forces, it is clearly observed that isotropic hardening overestimates the vertical roll forces since material hardens continuously when using this model. The total roll force is 6% higher when using the isotropic model. The maximum error is obtained in the 7th roll, being the roll force 23% higher in comparison to the kinematic model. In terms of roll torques, results are comparable to the force values. The total roll torque is very similar for both models and is 2% higher for the isotropic model. Regarding each roll torque, the biggest differences are located in the 4th and 5th rolls, where the isotropic model predicts a 10% and 13% higher torque values respectively.

The numerical results indicate that using the appropriated hardening model is especially important for the estimation of the roll forces and the dimensioning of the machine frame. Roll torque differences are not so substantial and thus the motor power selection is not critically affected by this input variable. Maximum thickness plastification prediction is unlikely affected by this input variable.

Acknowledgments

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