

SKIN-PASS PROCESS ANALYSIS THROUGH FINITE ELEMENT MODELS

Pernía, A.^(p); Vergara, E.; Lostado, R.; Escribano, R.; González A.

Abstract

The skin-pass is a cold-rolling process located at the final stage of the steel strip manufacturing line. Its main objective is to modify the strip material properties and its surface structure to be suited for the post forming operations as deformations, welding and painting. This work is focused on the analysis of the Skin-pass process through Finite Element Models (FEM) in order to obtain the influence of the parameters involved. In this way would be possible to establish optimization criteria for the process. The modeling of the skin-pass is somehow a challenge as there are important factors as: highly localized deformations; non-circular work-roll behaviour and elasto-plastic characteristics on the roll-gap area, difficult to model. The software used to model the process was ABAQUS®.

Keywords: Skin pass, finite element modelin, steel manufacturing process.

Resumen

El skin-pass es un proceso de laminado en frío ubicado en la etapa final de la línea de producción de chapas de acero. Su objetivo principal es el de modificar las propiedades mecánicas y la estructura superficial de la chapa para que tenga las características adecuadas, importantes en los procesos posteriores de deformación, soldadura y recubrimiento con pintura. Este trabajo se centra en el análisis de proceso de skin-pass mediante modelos de elementos finitos (FEM) para determinar la influencia de cada parámetro involucrado y de esta forma determinar criterios de optimización del proceso. El modelado del skin-pass representa un reto debido a la intervención de factores tales como: deformaciones altamente localizadas; comportamiento no circular de la superficie de los rodillos de trabajo y características elasto-plásticas de la zona de mordedura rodillo-chapa, difíciles de modelar. El software utilizado para modelar el proceso fue ABAQUS®.

Palabras clave: Skin-pass, modelado por elementos finitos; procesos de fabricación de acero.

1. Introduction

In the automotive industry materials are used in the form of thin metal sheet to obtain a large number of components through the stamping process (doors, bonnets, etc). The material of these thin plates must have the appropriate mechanical properties to avoid defects in the post forming processes as Lüder's lines or "orange peel".

The mechanical properties of the material are modified during cold rolling processes like skin-pass or temper rolling. Through these processes the final yield stress, yield elongation, flatness and residual stresses are changed depending on the degree of plastic deformation applied to the steel strip. For example, in the experimental work of reference [1] was possible to verify that according to the degree of plastic deformation of processes such as skin-pass the yield stress of the steel was highly amended.

The skin-pass consists on a combination of controlled compression and tension processes over the strip, applied through rollers. The evolution of the yield stress related to the degree of compression is displayed in Figure 1.

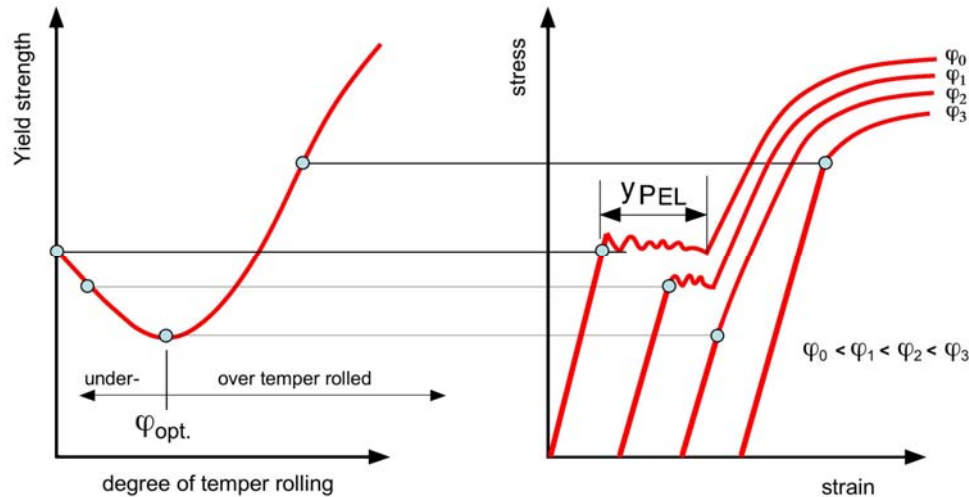


Figure 1. Modification of the mechanical properties of steel through processes of Skin-pass (courtesy of BFI).

As can be seen in the Figure 1, there is an optimum degree (φ_{opt}) for the process, and is reached when the yield elongation (y_{PEL}) is eliminated.

The modeling of the skin-pass represents a challenge as there are complicated factors to be simulated as: highly nonlinearities in the material behaviour; sever contact and friction conditions; consideration of the rolls as deformable entities, among other.

The aim of this work was to present to the readers some of the important factors to consider when to obtain an accurate model of the skin-pass process. We will focus on the material model and the first approach to the skin-pass simulation in two dimensions. The software used for the FE simulations was ABAQUS® [2].

2. State of the art

The skin pass have been increasingly modeled by FEM in the previous and present decade. Also, it is important to point out that the leader commercial software used to implement de FE models is ABAQUS®. Kijima and his colleagues [3] have studied the skin-pass processes using a 2D plane strain formulation and implementing half of the model because of the geometric and load symmetry. However, they considered the roller as a rigid body. They study has focused primarily on the acquisition of non-homogeneous distribution of deformation appearing on the inside and outside of the strip in terms of values as friction factor and load-thickness ratio. Other authors like [4], went further and considered the roller as a deformable body with elastic properties, meanwhile the strip is a deformable body with elasto-plastic properties. Reference [5], also take into account the deformation of the rollers and characterize the roll gap (contact strip-roller zone) conformed by elastic and plastic regions.

One of the main problems when simulate a process like skin-pass is the modelling of the material behaviour. A good reference of an accurate modeling of the material behaviour would be the work of Yoshida [6]. They developed a new FEM code and implemented it with

a material model based on the theory of Chaboche [7]. Through this procedure was possible to simulate the softening and hardening suffered by the material submitted to the skin-pass processes. Other authors as Morris [8] have noticed that in the process of skin-pass the yield stress suffers some changes similar to those occurred in low cycle fatigue processes. In this way they studied the cyclic response on stress-strain tests that revealed combinations of softening and hardening on the material. Authors such as Montmitonnet [9] went even beyond and developed different models of the material: elastic-plastic, elastic-visco-plastic and thermo-elastic (which also take into account the increase in temperature experienced by the material under cold rolling). He also suggested studying the process not only in steady-state, but in transitory state due to mechanical vibrations and chattering effects. As expected, the resulting mathematical model that includes all these characteristics, even though has enormous capabilities, has a very complicated structure, difficult to implement.

3. Study of the material model for the steel sheet

The knowledge of material behaviour is basic to carry out an engineering project. Knowing the elastic module and the elastic limit is enough in a lot of mechanic engineering project, because the yield is not desirable in structures and machines. However, the material acquires his form by plastic deformation in manufacture process (rolling, forge, etc). Therefore, the right plastic model that considers the phenomena involved in the skin-pass process has to be applied.

3.1 Elastic behaviour

The elasticity is the material property to deform with loads and recover their original form when load action stops. In this case, the elastic behaviour of the material during skin-pass process is the well known relation of the stress and the strain through the elastic module or Young module:

$$\sigma = E \cdot \varepsilon \quad (1)$$

3.2 Plastic behaviour

A plastic material behaves in elastic way until it reaches the elastic limit, moment in which the material behaves plastically. The simplest theoretical case is the perfect plasticity behaviour which consists in a deformation without load increase. Its graphical representation is presented below (Figure 2).

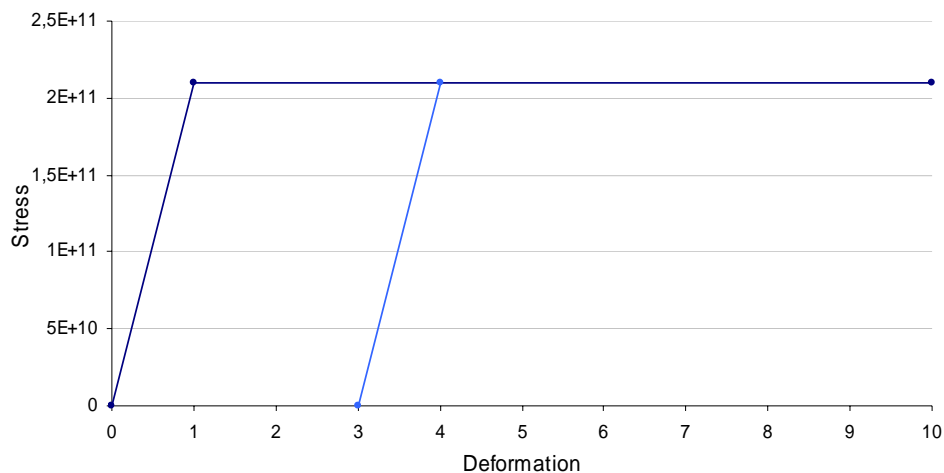


Figure 2. First cyclic response of a perfect elasto-plastic material.

When the load action stops, the material recovers the elastic deformation but it does not recover the plastic deformation. The elastic deformation is represented with azure line.

The criterion most convenient to predict the plasticity beginning is the Von Mises criterion in ductile materials. This says that the plasticity in a point is produced when the distortion energy reaches the deformation energy in a traction test. It's proved that the plasticity is reached when the equation is true:

$$\sigma_Y = \sqrt{\frac{1}{2}((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2)} \quad (2)$$

where σ_1 , σ_2 and σ_3 are main stresses in a point and σ_Y is the yield stress or elastic limit. The graphical representation of Von Mises criterion is presented in Figure 3.

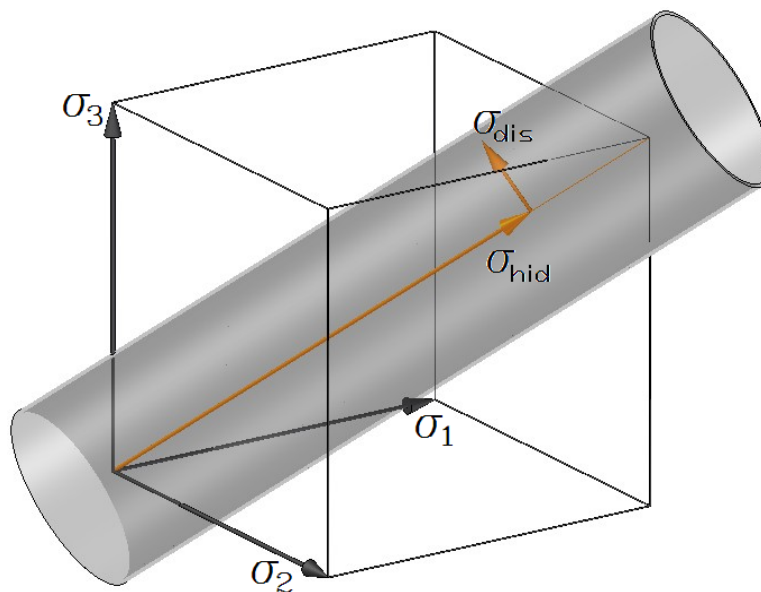


Figure 3. Yield surface base on von Mises criterion.

The axis σ_1 , σ_2 and σ_3 represent the main stresses, σ_{hid} is the hydrostatic stress and σ_{dis} is the distortion stress. General stresses can be decomposed into a hydrostatic and a deviatoric part. The hydrostatic stress vector is the cylinder axis and represents the yield surface. The plasticity would be produced only by the distortion stress part of the total stress. If distortion stress vector goes out of cylinder, the yield occurs.

3.2.1 Isotropic hardening

In this case, the plastic deformation is not a horizontal line but is oblique line or curved line, representing hardening or softening. In Figure 4 can be seen this behaviour.

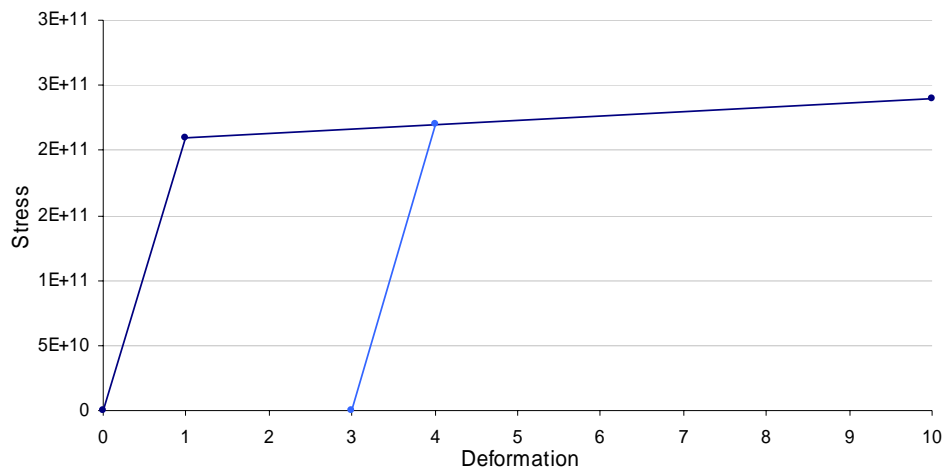


Figure 4. First cyclic response of an elasto-plastic isotropic hardening material.

It is same to say that the material suffers hardening or softening with plastic deformation. If the line is ascending the material hardens and if it is downward the material softens.

Looking along the space diagonal (hydrostatic component) to the center of the coordinate system of the von Mises yield surface, only the deviatoric part can be seen. This is represented in Figure 5.

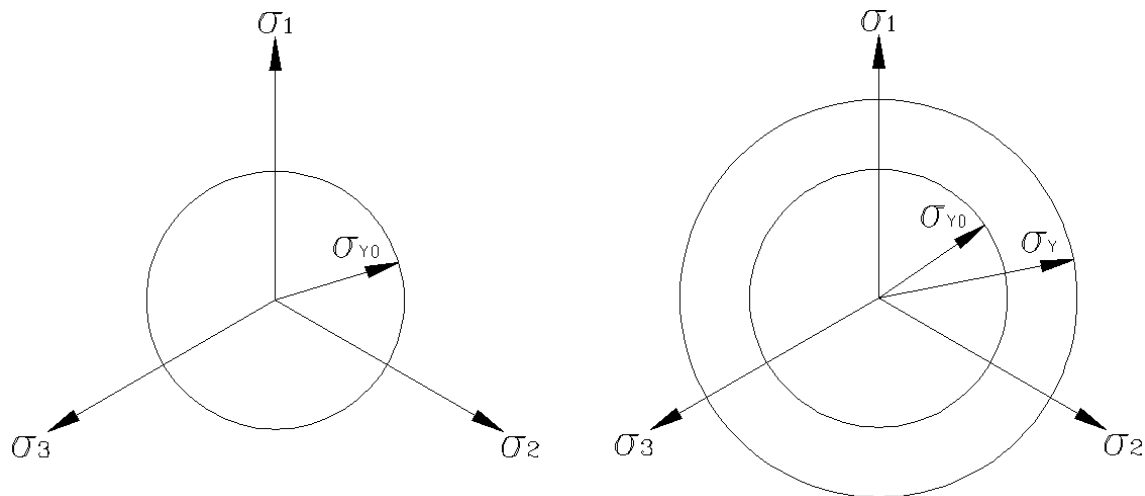


Figure 5. Change of the yield surface due to isotropic hardening.

The left drawing represent the original yield surface and the right one represent the new yield surface after plastic deformation occurs. As the new circumference has only changed its radius and has conserved the center, it is said that the plastic behaviour is isotropic. The radius of yield surface σ_Y can be calculated by:

$$\sigma_Y = \sigma_{Y0} + Q(1 - e^{-b\bar{\epsilon}_p}) \quad (3)$$

where:

- σ_Y is the radius of yield surface, this is the elastic limit,
- σ_{Y0} is the radius of original yield surface, this is, original elastic limit,
- Q is the highest increment of radius that the material can undergo,

- b is the increment ratio,
- $\bar{\varepsilon}_p$ is the equivalent plastic deformation.

2.4 Kinematic hardening

In this case, the yield surface displaces its center as can be seen in Figure 6.

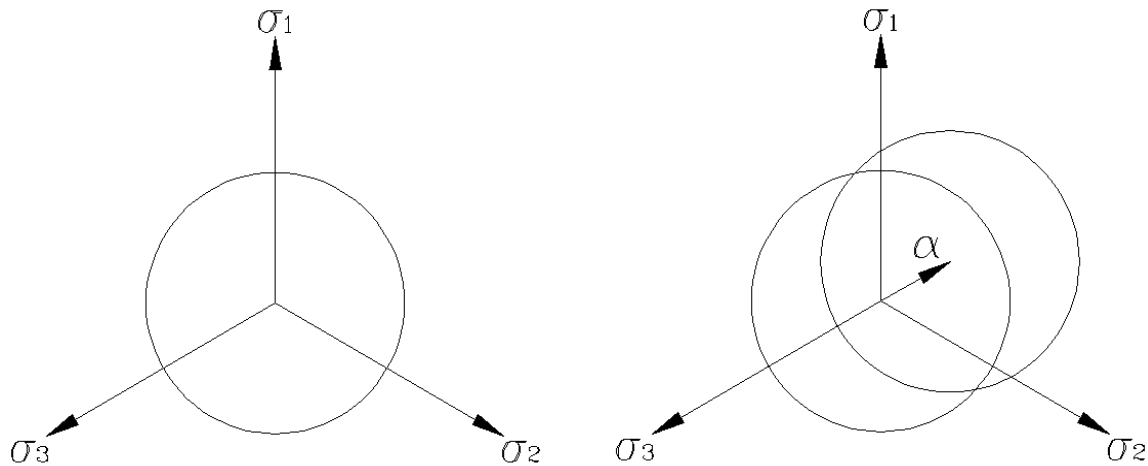


Figure 6. Change of the yield surface due to kinematic hardening.

The displacement velocity of the surface's centre or flow rule is:

$$\dot{\alpha} = C \frac{1}{\sigma_Y} (\sigma - \alpha) \bar{\varepsilon}_p - \gamma \alpha \bar{\varepsilon}_p \quad (4)$$

where:

- $\dot{\alpha}$ is the displacement velocity of surface centre.
- C is the initial cinematic hardening module,
- σ_Y is radius of yield surface,
- σ is the plastic tension,
- α is the position of yield surface centre,
- γ is the decrease ratios of cinematic hardening module,
- $\bar{\varepsilon}_p$ is the equivalent plastic deformation.

3.2.2 Combined hardening

The combined hardening behaviour is the sum of the isotropic plasticity and kinematic plasticity.

In the Figure 7 we can see a strain-stress graphic of a point in a solid subjected to cyclic load that changes between zero and positive value.

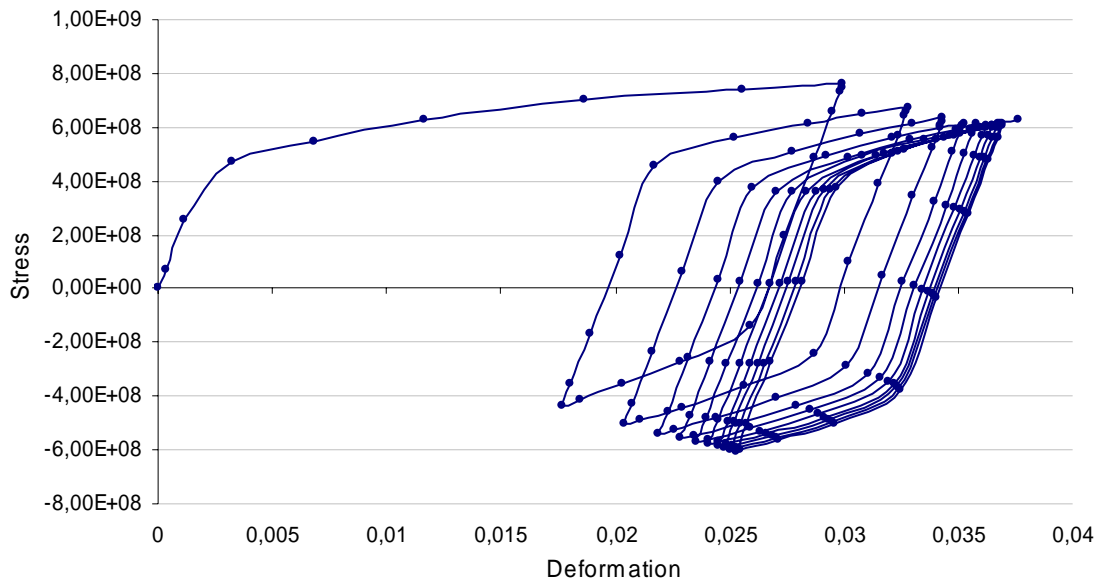


Figure 7. Cyclic response of a material with combined plasticity.

Several characteristic scan be seen from this experiment:

- An elastic strain and later a plastic strain in every cycle are presented.
- The kinematic hardening-softening phenomenon is represented by each cycle's vertical variation. First a softening an afterward a small hardening is observed (the same behaviour presented in Figure 1).
- The flow rule trend to stabilize as the cycles passes. This is represented by the cycle's proximity at the end of the experiment.

Chaboche [7] went further and created a model that splits the surface center change (α) in an arbitrary number of components, i.e.:

$$\alpha_{ij} = \sum_{n=1}^M \alpha_{ij}^n \quad (5)$$

followed by

$$\dot{\alpha}_{ij}^n = \frac{2}{3} C^n \dot{\epsilon}_{ij}^p - \gamma^n \alpha_{ij}^n \dot{\epsilon}_{eq}^p \quad (6)$$

where C^n and γ^n are material parameters that must be calibrated from cyclic test data. The C^n represent the initial kinematic hardening modulus, and γ^n determines the rate at which the kinematic hardening modulus decreases with increasing plastic deformation.

This model takes into account several important material behaviours as: Bauschinger effect, cyclic hardening with plastic shakedown and ratchetting, and therefore is the one used in many references to simulate plastic behaviour. To have an idea of the possibilities of the Chaboche model, in the following figure (Figure 8) a comparison of the different plasticity models is presented.

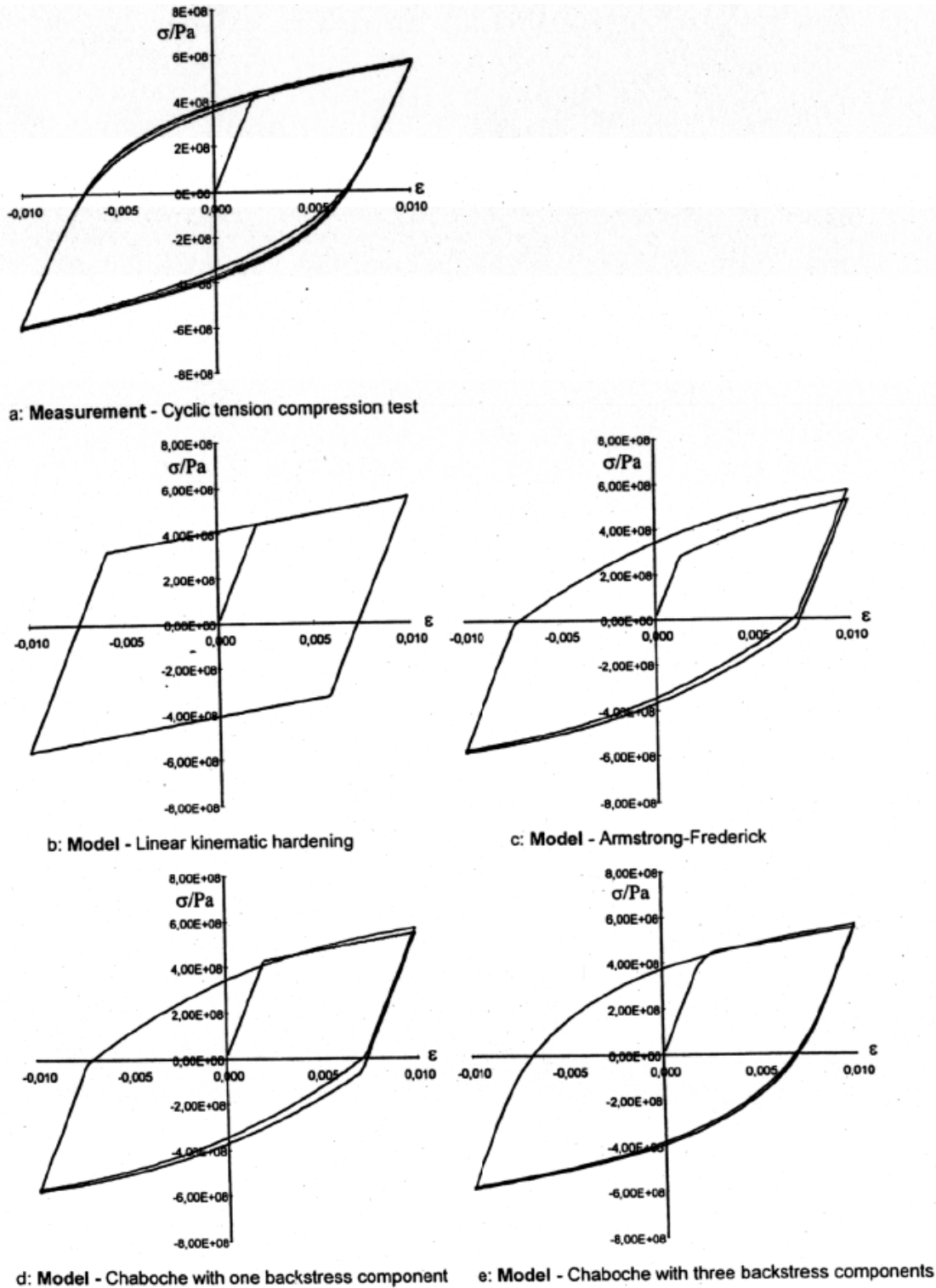


Figure 8. Comparison of several plasticity models for a cyclic tension-compression test (figure taken from Schleinzer [10])

In this figure, it is possible to observe how the Chaboche models resembled the experimental result in an accurate way.

The procedure to obtain the parameters of the model (C^n , γ^n , Q , b , γ^n) are exposed in a clear way in reference [10]).

Therefore, the Chaboche model seems to be the suited one to apply in the skin-pass modeling.

4. Skin-pass 2D FEM

The real problem has symmetry along the vertical axis and therefore can be seen in 2 dimensions, where only one roll (upper roll) and half of the sheet is represented. Symmetry boundary conditions were applied at the base of the sheet.

As the velocities involved in the process are low, the model could be implemented in the ABAQUS/Standard – Static, General. In further researches, the implementation of the model in ABAQUS/Explicit will be tested.

For the 2D model CPE4R (plane strain element, 4-node bilinear, reduced integration with hourglass control) elements were used. The rollers were generated using 'Analytical Rigid Surfaces'. Also, the rollers were simulated as not driven roller. For this propose rotary inertia was included in each roller depending on its physical characteristics (density and volume). The friction coefficient between the roller and the sheet was set to 0.2.

As a result, the roller was simulated as a rigid body while the sheet was the deformable body.

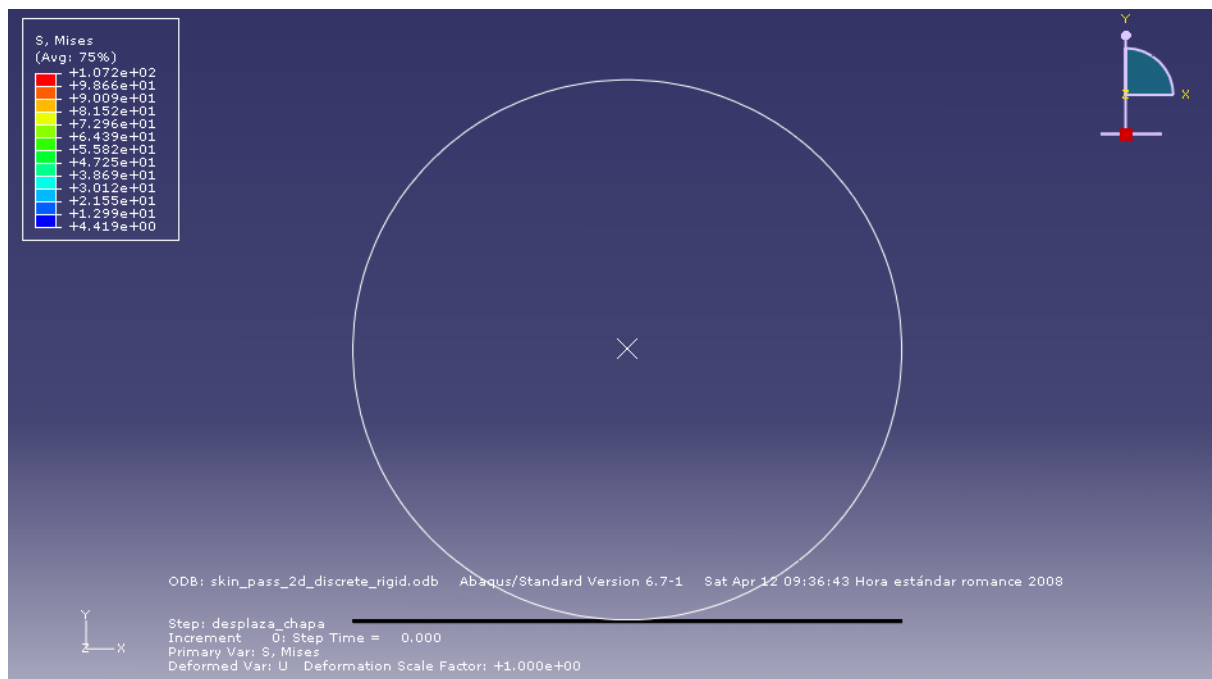


Figure 9. Symmetric model of the roller and the sheet.

The simulation is divided into three stages: the first one is a preload of the sheet, followed by a compression of the sheet through the rigid roller (around 1% of the sheet thickness) and, finally, the displacement in the horizontal plane of the sheet at a constant velocity. The last stage produces the roller rotation, thanks to the friction that exists between the sheet and roll.

The simulations over this model intended to understand the fundamentals involved in the skin-pass process. In the next figures some results are presented.

The von Mises stresses are presented in Figure 10.

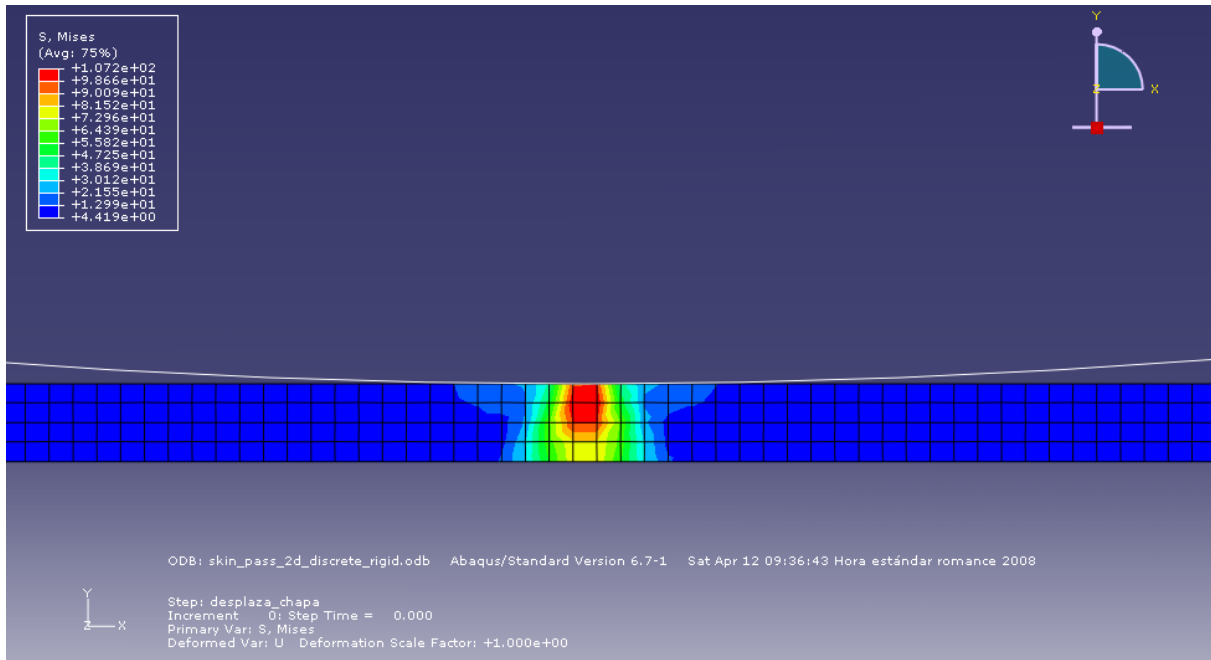


Figure 10. Von Mises Stress after the deformation of 1% of the sheet thickness.

In this case the maximum stress is 107 MPa, below the yield stress of the steel grade studied (260 MPa). Therefore, only elastic deformations will be observed. In further research the plastic behaviour with the combined model will be studied.

In the next figure, the normal forces in the sheet can be observed. The step in the figure is produced at 2 units of times, which is the time when the roller compressed the sheet.

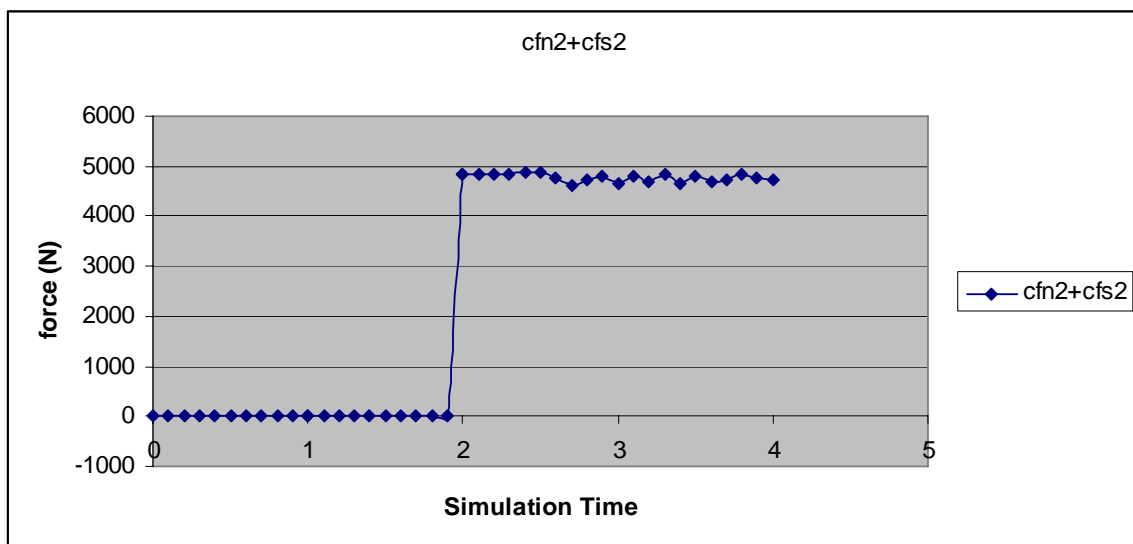


Figure 11. Total normal forces on the sheet.

In these conditions, the maximum total normal force was 5 KN. This information could be used for the design of the roller axle.

In the same way, the total tangential forces on the sheet were obtained (Figure 12).

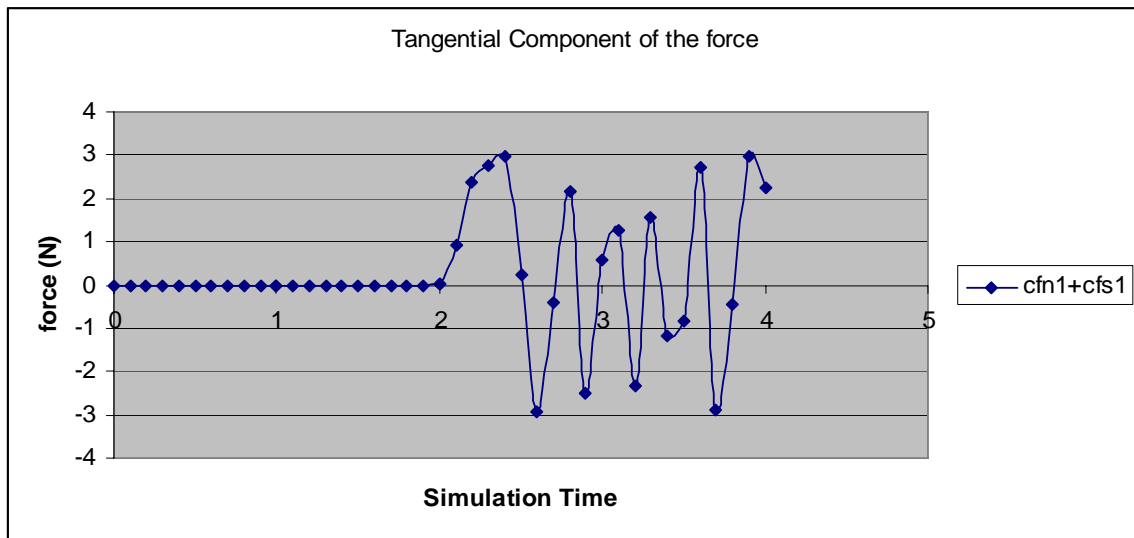


Figure 12. Total tangential forces on the sheet.

The magnitudes in this case were very small due to the ideal representation of the roller axle. It was modeled as a perfect axle (without friction), therefore, the reaction forces are null. Nevertheless, in further simulations, the roller axle could include a friction coefficient.

5. Conclusions and further research works

A first view of the problematic on modelling the skin-pass process was presented. A review of the different plasticity models was exposed, concluding that the nonlinear kinematic hardening model of Chaboche will be the suited one to represent the material behavior during the process. Also the first 2D model of the process were described. For further works deeper studies will be carried out:

- 2D simulation with linear elastic sheet's material behaviour and deformable elastic roller.
- 2D simulation with Chaboche sheet's material behaviour and rigid roller.
- 3D simulation with linear elastic sheet's material behaviour and deformable elastic roller.
- 3D simulation with Chaboche sheet's material behaviour and rigid roller.

References

- [1] Hoggan E. J., Scott R. I., Barnett M.R., Hodgson P.D., "Mechanical properties of tension levelled and skin passed steels", *Journal of Materials Processing Technology*, Vol. 125-126, 2002, pp. 155-163.
- [2] ABAQUS Analysis User's Manual, version 6.5. 2005.
- [3] Kijima H., Bay N., "Contact Conditions in Skin-pass Rolling", *Annals of the CIRP* Vol. 56/1, pp. 301-306, 2007.
- [4] Kainz A., Krimpelstätter K., Zeman K., "FE - Simulation of Thin Strip and Temper Rolling Processes", ABAQUS Austria Users' Conference, November 24-25, 2003, Vienna.
- [5] Krimpelstaetter K., Hohenbichler G., Fistermann G. and Zeman K., "New non-circular arc skin pass model", *Ironmaking and Steelmaking*, 2007.

- [6] Yoshida F., Urabe M. "Computer-aided process design for the tension levelling of metallic strips", *Journal of Materials Processing Technology*, vol. 89-90, 1998, pp. 218-223.
- [7] Chaboche J. L., Rousselier G., *Trans ASME J. press.*, Vessel Tech. v. 105, 1983, pp.153.
- [8] Morris J. W., Hardy S. J., Lees A. W., Thomas J. T., "Cyclic behaviour concerning the response of material subjected to tension levelling", *International Journal of Fatigue*, vol 22, 2000, pp. 93–100.
- [9] Montmitonnet P., "Hot and cold strip rolling processes", *Comput. Methods Appl. Mech. Engrg.* Vol. 195, 2006, pp. 6604–6625
- [10] Schleinzer Gerard, Residual Stress Formation During the Roller Straightening of Rails, Fortschr.-Ber. VDI Reihe 18 nr. 251. Düsseldorf: VDI Verlag. ISBN 3-18-325118-3, printed in Germany, 2000.

Acknowledgements

The authors would like to thank to the European Union for the financial support for the project RFS-PR-06035 and the "Dirección General de Investigación" of the Spanish Ministry of Education and Science of the projects DPI2006-03060, DPI2006-14784, DPI-2006-02454 and DPI2007-61090. Finally, the authors also thank the Autonomous Government of La Rioja for its support through the 3^o Plan Riojano de I+D+i.

Corresponding Author (For further information, please contact to):

Alpha Pernía Espinoza
Grupo EDMANS
Área de Proyectos de Ingeniería.
Departamento de Ingeniería Mecánica.
Edificio Departamental. Universidad de La Rioja.
C/ Luís Ulloa 20, 26004 Logroño-La Rioja (España).
Phone: +34 941 299 517 / 232
Fax: + 34 941 299 794
E-mail: alpha.pernia@unirioja.es
URL: <http://www.mineriadatos.com>