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# Reduction of flatness defects in thin metal sheets by a pure tension leveler

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## ABSTRACT

In metal industries (aluminum, steel,…), the flatness defects of the thin strips can be corrected by pure tension leveling. This process is able to minimize the residual stresses from rolling step by plastically lengthening the metal sheet. This paper introduces a numerical modeling of strip conveying through a simplified industrial leveler (composed of four rolls), using a commercial FEM software. It includes shell elements discretization and frictional contact between strip and rolls. From plastic strains and residual stresses through width and thickness, the final strip shape is predicted. The *Finite Element* model shows how an entering strip with a flatness defect (manifested or latent) is transformed at the leveler exit: waves are decreased and longitudinal stresses gap is reduced.

## 1. Introduction

Aluminum is a material very widespread in many industrial domains like aeronautics, automotive, construction or packaging. From a thick ingot, coil of thin strip is produced by hot rolling then by cold rolling. Thickness reduction is obtained by several passes between the work rolls. But the rolling mill may deform due to the huge stresses involved or to thermal changes in such a way that heterogeneous strains and stresses are created in the strip's width and thickness, so called flatness defects. They are grouped into two types (see Fig. 1):

- “fiber defects” like *long middle* or *long edge*. For the first one, longitudinal fibers are longer in the central region than near the edges. Due to this discrepancy, some compressive stresses exist in the middle whereas edges are stretched. Then waves might appear where compression occurs due to buckling phenomenon (Fischer et al., [4]).
- “curvature defects” like *coil set* or *crossbow*. This kind of defect is due to a length difference through thickness between either longitudinal fibers for *coil set* or transverse fibers for *crossbow*.

Therefore a leveling operation has to be added after rolling to correct these defects and to satisfy the users' stringent flatness requirements. The principle of this process consists of plastically elongating the metal strip with the aim of bringing all the longitudinal and tranverse fibers to the same length (Roberts, [18]). Levelers are complex machines constituted by a collection of rolls with different diameters which cancel the unreceivable flatness defects (see Fig. 2). *Pure tension leveler*, also called *stretcher*, plastically elongates the strip only by tension thanks to two *bridle rolls*, one at the entrance which raises the strip tension beyond the metal yield stress, one at the exit which has to decrease it. *Multiroll leveler* introduces plastic strain with alternate bending. They are formed by two slides of rolls of the same small diameter, an inferior one which is fixed and remains horizontal, a top one which can be tilted and vertically moved to produce a decreasing tightening of the strip. Only a fraction of the thickness is plastified. *Tension leveler* combines alternate bending under tension which leads to more plastification through thickness and the possibility to correct more flatness defects than the previous machines.

Few papers studied the leveling process with analytical or numerical approaches to understand the different parameters influence on the strip flatness and the residual stresses.

In spite of simplifying assumptions, (semi-)analytical models are able to provide the stress and strain distributions through thickness, and the strip residual curvatures in a very short time. They may be sufficient to understand the important mechanisms of leveling process, to bring adjustments for flatness optimization or residual stresses reduction, and even to be used in a control system. Swift [21], Kinnavy [9] and Patula [17] studied the strip bending under tension so as to predict longitudinal strain and tension loss due to fibers plastification. Doege et al. [3] carried out an analysis of the *tension leveling* process in two dimensions based upon an analytical model in which the curved metal strip was considered as a beam. Industrialists were also focused on leveling comprehension to build up adjustments table for their machines thanks to an analytical approach elaborated by Bourgon

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**Nomenclature**

| | |
|---|---|
| $x$ | Coordinate in longitudinal direction |
| $y$ | Coordinate in transversal direction |
| $z$ | Coordinate in normal direction |
| $R$ | Radius of rolls (*mm*) |
| $d$ | Distance between rolls' centers (*mm*) |
| $w$ | Width of aluminum strip (*mm*) |
| $t$ | Thickness of aluminum strip (*mm*) |
| $l$ | Size of the stretcher (*mm*) |
| $\alpha$ | Contact angle between strip and roll (*rad*) |
| $\underline{\underline{C}}$ | Elasticity tensor |
| $E$ | Young's modulus of aluminum (*MPa*) |
| $\sigma_0$ | Yield stress of aluminum (*MPa*) |
| $c_0$, $p_0$ | Parameters for the exponential law from normal contact |
| $\mu$ | Friction coefficient |
| $\sigma_1$, $\sigma_2$, $\sigma_3$, $\sigma_4$, $\sigma_5$ | Longitudinal stresses from different parts of the stretcher (*MPa*) |
| $V_1$, $V_2$, $V_3$, $V_4$, $V_5$ | Strip velocity from different parts of the stretcher ($mm.\ s^{-1}$) |
| $\omega_1$, $\omega_2$, $\omega_3$, $\omega_4$ | Roll rotation speed ($rad.\ s^{-1}$) |
| $\varepsilon_1$, $\varepsilon_2$, $\varepsilon_3$, $\varepsilon_4$, $\varepsilon_5$ | Longitudinal strains from different parts of the stretcher |
| $IU^{geom}$ | Geometric flatness defect expressed in *International Units* (*IU*) |
| $\Delta L$ | Length difference between long and short longitudinal fibers (*mm*) |
| $L$ | Mean length of fibers (*mm*) |
| $A$ | Amplitude of flatness defect considered as a sine curve (*mm*) |
| $\lambda$ | Wavelength of flatness defect considered as a sine curve (*mm*) |
| $IU^{lat}$ | Latent flatness defect expressed in *International Units* (*IU*) |
| $IU^{pl}$ | Numerical flatness defect expressed in *International Units* (*IU*) |
| $\sigma_T$ | Longitudinal tension applied to the strip (*MPa*) |

et al. [1] and Gevers et al. [6]. Strip was discretized in several beams throug width and about fifty slices through thickness. The authors computed the thickness plastification rate at passing on the rolls, longitudinal and transversal stresses through width and thickness, and also the residual curvatures. More recently, Liu et al. [11] proposed a model for predicting the *multiroll leveling* process of plates, based on the curvature integration method, with a linear strain hardening material behavior. The approach was validated by comparison with experimental data and showed that the contact angles between strip rolls were very important points for residual stresses determination. Galdos et al. [5] also studied *multiroll leveling* with two models, a 2D FEM with *MSC Marc* software (mixed hardening law, friction coefficient to ensure strip pulling by rolls rotation) and a 1D analytical model (beam bending theory, elastic perfectly plastic behavior). Both approaches were verified with a 13-rolls leveler prototype. Plastification rate through thickness, leveling force and torque were pointed out.

Numerical simulations with *Finite Element Method* are more accurate, without symplifying assumptions but computational time highly raises with the requested precision and the process characteristics taken into account in the model. Thus they are rather used offline. Morris et al. [15] were interested in *tension leveling* (five rolls) and conducted numerical tests to evaluate the parameters importance on the strip final flatness. The wrap angle on the second last roll was found to be the most influent parameter. Huh et al. [7] used commercial software *Abaqus/Standard* to build a 2D *FEM* model for a *tension leveler* in order to choose the design parameters like tension, roll intermesh, roll pitch, number and diameter of rolls. In the same way Trull [22] also simulated the *tension leveling* process but in 3D with a strip discretization by linear shell elements, whereas rolls were supposed to be analytical rigid surfaces. The five steps simulation (tension application, rolls descending, strip conveying, rolls rising, tension release) needed two days to be computed. The longitudinal plastic strain was almost constant through width, except near the free edge where it slightly decreased. This effect was impossible to predict with only 2D models and showed the importance of in-width simulations despite an apparent homogeneity of the process along this direction (flat rolls, no friction, uniform tension,…). For an incoming strip with an initial geometric flatness defect, the model showed also that the leveler corrected it by damping the fibers lengths difference. Li et al. [10] recommanded also a 3D *FEM* model for this kind of process. They chose *MSC Marc* software and added a frictional contact. Mathieu et al. [12] studied only an elementary part of a leveler called *bridle rolls*. A 3D *Finite Element* model was proposed with *Abaqus/Standard* commercial software with shell element discretization, frictional contact consideration and strip conveying simulation.

In this paper, we propose to focus on a different leveler configuration (*pure tension leveling* is almost never studied in the literature) in which friction between strip and rolls is very important. The aim of the present work is to establish a numerical modeling of a *stretcher* in three dimensions in order to evaluate plastic strain and residual stresses distributions through the strip width and thickness. Also strip flatness prediction at the end of the process is aimed. Moreover, the important point of this work is to verify the corrective capacity of the machine with introducing initial geometric and latent defects (whereas Mathieu et al. [13] tried to propose an alternative model based on the machine decomposition and data transfer). To fulfill this purpose a 3D *Finite Element* model is developped with *Abaqus/Standard*.

## 2. A 3D *Finite Element* model for the stretcher

### 2.1. Model description

The *pure tension levelers*, also called *stretchers*, can correct flatness defects thanks to plastic strain only due to tension. They are made up of two bridle rolls, one at the entrance, one at the exit. In this paper, the simplest existing configuration is studied: a *stretcher* with only four rolls (even if common machines contain rather eight or ten rolls). It allows an increase then a decrease of the strip tension considering contact with friction. Between first and second bridle rolls the strip tension is beyond the material yield stress to introduce plastic strain. Leveler and strip geometric characteristics are presented in Fig. 3 and Table 1.

To simplify the problem, the *stretcher* rolls are supposed to be

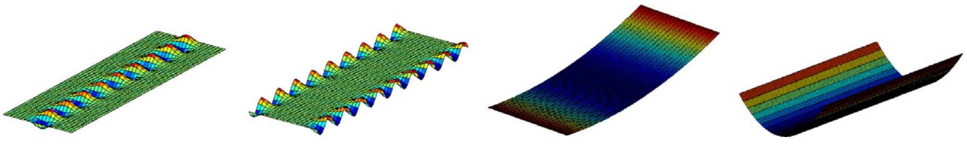
(a) Long middle (b) Long edge (c) Coil set (d) Crossbow

**Fig. 1.** Flatness defects.