Manifested flatness predictions in thin strip cold rolling

S. Abdelkhalek[1], P. Montmitonnet [1], N. Legrand [2], P. Buessler [2]

[1] *Ecole des Mines de Paris-ParisTech- CEMEF - UMR CNRS 7635 - BP 207 - 06904 Sophia-Antipolis - Cedex - France*
URL: www-cemef.cma.fr e-mail: sami.abdelkhalek@ensmp.fr ; pierre.montmitonnet@ensmp.fr

[2] *ArcelorMittal Research, R&D Industrial Operations - BP 30320 - Voie Romaine 57283 Maizieres Les Metz -Cedex- France*

URL: www.arcelormittal.com e-mail: nicolas.legrand@arcelormittal.com

ABSTRACT: The paper deals with flatness defects prediction in thin plates which appear during rolling. Their origin is the roll stack thermo-elastic deformation. The combination of the elastic deflection, the thermal crown and the roll grinding crown results in a non-parallel bite. If the transverse roll profile is not an affinity of the incoming strip profile, differential elongation results and induces high stresses in the outgoing strip. The latter combine with the imposed strip tension force, resulting in a net post-bite stress field which may be sufficiently compressive locally to promote buckling. A variety of non-developable shapes may result, generally occurring as waviness, and classified as flatness defects (center waves, wavy edges, quarterbuckles…). The purpose of the present paper is to present a coupled approach, following [1] : a simple buckling criterion is introduced in the FEM model of strip and roll deformation, LAM3 / TEC3 [2]. The post-bite stress field is in much better agreement with experiments if this treatment is used, as will be demonstrated.

Key words: Sheet metal; Rolling; Flatness defects; Residual stresses; Buckling;

1 INTRODUCTION

Flatness defects are one of the major problems encountered in strip rolling. Their origin is out-of-bite stress gradients resulting in buckling in the compressive stress areas. Depending on the stress component involved and the location of compressive areas, waves in the longitudinal, transverse or oblique directions can be found, at diverse locations (Long edge / centre, quarter-buckles… see figure 1). In turn, these pre- and post-bite stress gradients have their origin in the differential elongation due to the combination of incoming strip crown and work roll (WR) active profile. The latter is a combination of grinding crown, thermal crown, and elastic roll stack and stand deformation.
During the rolling process, the strip is under tension from coilers or neighbouring stands. Hence, defects can be more or less dissimulated, but can be measured through the heterogeneity of stress distributions: latent defect. The latter becomes a manifested defect, or a manifested defect may amplify, when the strip tension is relaxed.

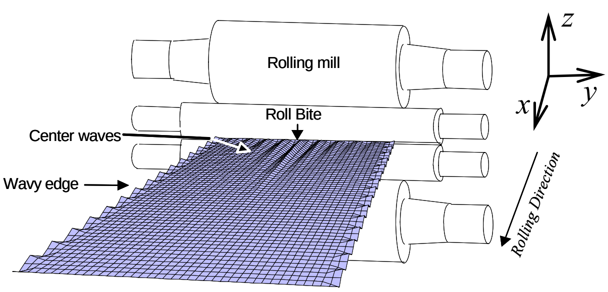

Figure 1. Schematic illustration of flatness defects [1].

2 SCIENTIFIC STAKES

The prediction of the occurrence and of the characteristics (wavelength, amplitude) of flatness defects is therefore a big challenge. A precise roll stack deformation model must be used; its input data, the strip / Work roll contact pressure field, must be accurate. This leads to favour thermo-mechanical, strip / roll stack coupled model. LAM3, a software developed by Cemef, Transvalor, Arcelor Research and Alcan [3], solves the strip elastic-viscoplatic

strain by 3D FEM, and the roll stack elastic deformation by semi-analytical models.
It must be realized that defects are generally non-symmetric, neither in the vertical nor in the transverse direction, and non-steady state: waves formed at bite exit, in a region of large stress gradients due to fast reorganization of the velocity field, are transported with the material velocity.
Moreover, manifested flatness defects imply thorough stress reorganization, because stresses always saturate in buckled areas. This complete rearrangement of the stress field in the post-bite strip can be viewed as a change in the boundary conditions of the plastic deformation in the bite. Hence, in-the-bite and out-of-bite stress fields may be strongly coupled. This makes questionable those models of flatness defects, in which a post-bite zone at some distance away from the roll gap is considered, where the stress field is quite moderate. The latter is first computed by an adequate FEM strip rolling model, then transferred to a structural, completely decoupled analytical or FEM model where buckling is analyzed [4] [5] [6].
A fully convincing model should therefore take into account all couplings: strip in the bite, buckling out-of-bite, roll stack, with mechanical and thermal fields. At this stage, a simple steady-state coupled model has been used [1]; but in this case, due to the non-steady state character of the waves, only the occurrence of waves can be predicted with a certain degree of certainty, not their severity.

3 SIMPLE COUPLED MODEL OF BUCKLING USED (COUNHAYE'S MODEL)

Following [1], we have introduced in LAM3 (steady state version) a stress-relaxation algorithm when a simple plate buckling criterion is met :

$$\sigma_c = \frac{\pi E h^2}{3\delta^2} \qquad (1)$$

E is Young's modulus, h the strip thickness, and δ the wavelength (assumed similar to the compressive stress area dimensions). Wherever a principal stresses σ_I or σ_{II} reaches σ_c, we assume buckling will shorten a material element in the corresponding direction by :

$$\lambda_I = \frac{\sigma_I - \sigma_c}{k \times E}$$

$$\lambda_{II} = \frac{\sigma_{II} - \sigma_c}{k \times E} \qquad (2)$$

$$k << 1$$

k is a parameter presenting the ratio between the material "buckling stiffness" and the Young modulus.
This decreases the strain sent back after each Newton-Raphson iteration to the constitutive model solver, and therefore the compressive stresses (and as a consequence, the stresses in the tensile area, to maintain mechanical equilibrium). This tends to force iteratively the stress field to respect the criterion.
Remark: λ_i (i = 1,2) can also been defined as a a deformation recovered by buckling, so it can be given by :

$$\lambda_i = \ln\left(\frac{\tilde{L}_i}{\overline{L}_i}\right), \ (i = 1,2) \qquad (3)$$

where $\tilde{L}_i$ and $\overline{L}_i$ are respectively the developed length of the buckled line and its projection on (x,y) plan.
Although buckling does not occur at element scale, here it is treated locally on each element reaching the critical stress estimated in (1). However, despite the simplicity of this model, figure 2 shows, for particular rolling conditions (Table 1), that the impact of buckling on the final stress state is to bring it closer to experiments (tensiometer roll). Furthermore, we note an insignificant dependence of results on σ_c value. This supports the criterion (1) in spite of its simplicity.

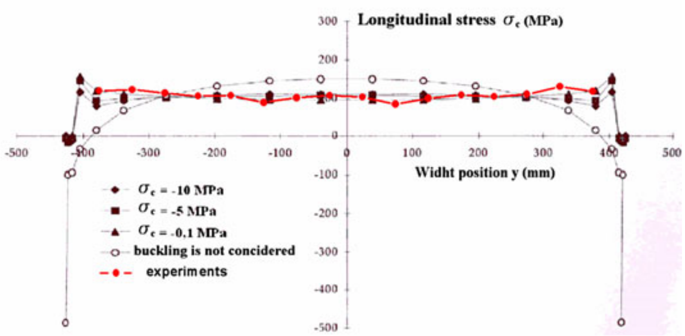

Figure 2. Comparison of stress profiles computed with and without accounting for stress relief by buckling, and measured in experiments [1] (far away enough from the bite).

Friction law	Coulomb : $\mu = 0.033$
width	851 mm
Entry thickness	0.355 mm
Looked thickness for	0.225 mm
Upstream imposed tension	170 MPa
downstream imposed tension	100 MPa
Rolling velocity	22 m.s-1
Work roll diameter	555 mm
Behaviour law	Young modulus E = 210 GPa Poisson 's ratio $\upsilon = 0.3$ $\sigma_0 = (470.5 + 175.4 \times \bar{\varepsilon})$ $\times (1 - 0.45 \times e^{-8.9\bar{\varepsilon}})$-175

Table 1. Simulated rolling operation description.

4 GENERAL FEATURES OF THE STEADY-STATE FINITE ELEMENT MODEL (LAM3/TEC3)

The global algorithm of thermomechanical computing is presented in figure 3. As the steady state model requires an integration of the stress history along material streamlines, a structured mesh composed of hexahedral (8-node brick) elements is used. It consists of a series of cross sectional meshes (4-node quadrilateral elements) with identical topology, progressing in the rolling direction. The streamline updating step (of both free surface and internal nodes) ensures that lines of nodes are located on streamlines.

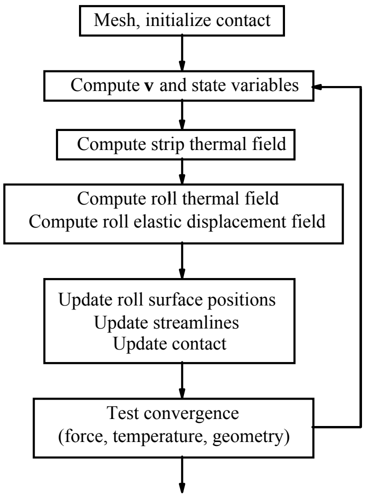

Figure 3. Global flow chart of the model.

In the second step ("Compute velocity v and state variables") it is assumed that integration points as well as nodes are aligned along streamlines, so that the stress integration may be performed from integration point to integration point.
In the iterative process pictured in figure 4, stress and strain are updated to respect the equilibrium equation on each integration point. At this stage, the simple buckling model has to be implemented in order to respect the buckling criterion given by (1) as exposed in figure 5.

5 RESULTS AND DISCUSSION

Several cases of steel and aluminium strip rolling were observed presenting comparable results. The case which was presented previously (table 1) has been reproduced in order to evaluate the validity of the model.
Similar to results exposed on figure 2, figure 6 shows that considering buckling brings our results closer to experiments.
As shown by figures 7 and 8, considering buckling does not change the contact stress in the bite (figure 7), nor the rolled strip profile (figure 8). Hence, at this stage of this study the bite/out-of-bite coupling does not seem so necessary. Further work will be devoted to this point.

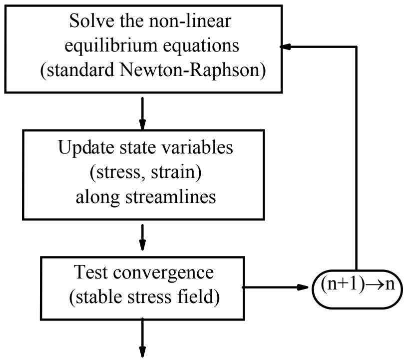

Figure 4. Flowchart for velocity field and stress field computation.

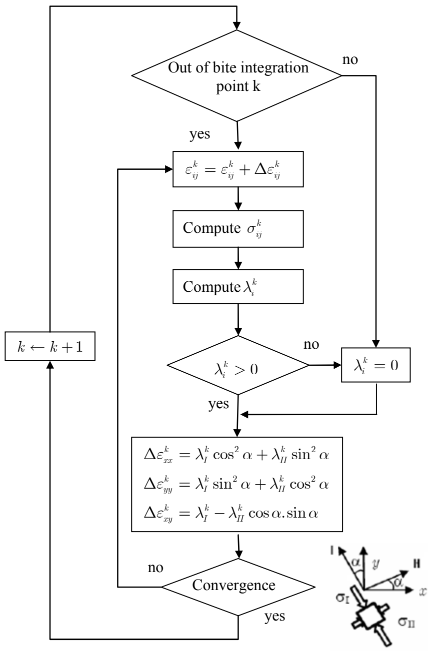

Figure 5. Algorithm of coupling Lam3/tec3 with a steady state simple buckling model: ε_{ij} and σ_{ij} are respectively the strain increment tensor and the stress components, α defines the principal directions *I* and *II* in the laboratory reference frame.

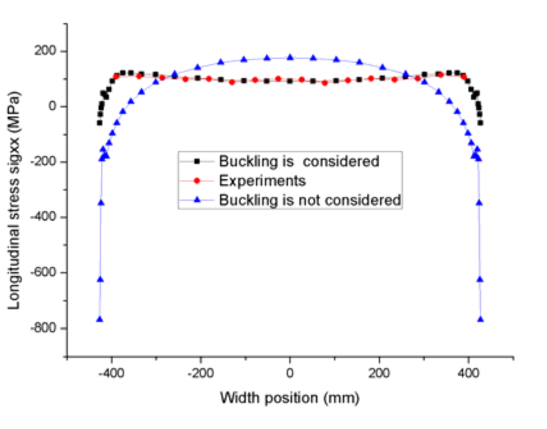

Figure 6. Longitudinal stress at enough distance away from the bite (case data: table 1) : σ_c=-10 MPa.

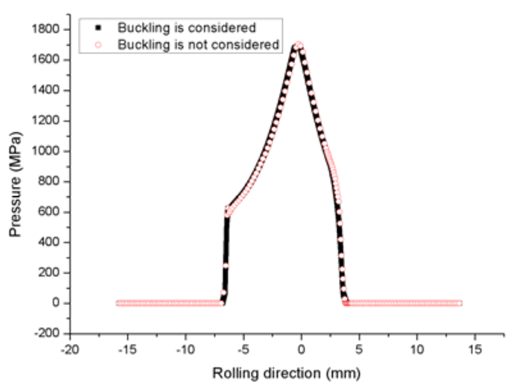

Figure 7. Centre line normal pressure in the bite (case data: table 1).

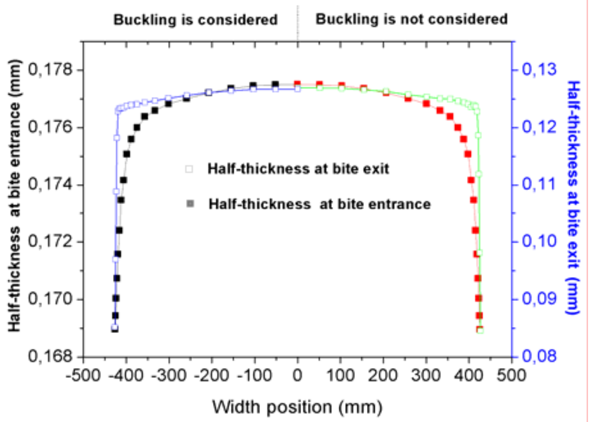

Figure 8. Rolled strip geometry at the exit and the inlet of bite (case data: table 1).

Therefore, a decoupled approach using a more sophisticated and general approach, the asymptotic numerical shell element model (ANM) [7], proves interesting. Several strip rolling cases have been modelled, one of them is presented in figure 9. The displayed strip shape at bite exit shows longitudinal stationary waves near the centreline. The ANM thus looks more promising, being a much more precise and predictive buckling model, in particular allowing modelling of post-buckling.

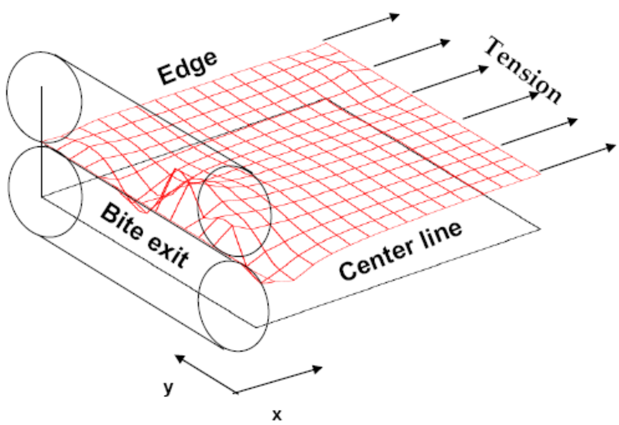

Figure 9. Uncoupled computed flatness defect for the case presented on table 1.

6 CONCLUSIONS

Lam3/Tec3 has been complemented with a simple buckling model, so that stresses are closer to experiments. Fortunately, the fact that the buckling has no influence on the bite, might avoid the difficult point of coupling Lam3/Tec3 (bite zone) and the ANM model. Yet, this finding has to be confirmed through numerical testing. Furthermore, if non stationary wavy edge defects are to be modelled completely, this coupling will probably prove necessary.

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