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Prediction of camber formation, suppression and control of wedge-shaped hot rolled slabs by analytical concepts and finite elements

A. Kainz*. T. Pumhoessel*, M. Kurz**, M. Widder***, L. Aigner****, K. Zeman*

*Institute of Mechatronic Design and Production, Johannes Kepler University Linz, A-4040 Linz, Austria
(e-mails: alexander.kainz@jku.at, thomas.pumhoessel@jku.at, klaus.zeman@jku.at)
**Primetals Technologies Germany GmbH, D-91052 Erlangen, Germany
(e-mail: matthias.kurz@primetals.com)
***Primetals Technologies Austria GmbH, A-4031 Linz, Austria
(e-mail: markus.widder@primetals.com)
****voestalpine Stahl GmbH, A-4031 Linz, Austria
(e-mail: larissa.aigner@voestalpine.com)

Abstract: For today's process automation systems for hot strip mills, wedge reduction without generating camber is still a big challenge. By utilizing suitably positioned edging rolls, the corresponding side force acting on the strip induces a lateral material flow inside the roll gap, leading to stress-redistributions such that the outgoing camber is drastically reduced. Systematic parameter studies performed so far by utilizing the commercial FEM-package ©Abaqus Explicit revealed the dependence of the lateral edging force and the resulting strip centerline-curvature on characteristic rolling parameters, such as slab width, thickness, initial wedge and thickness reduction. To understand the underlying highly non-linear elasto-viscoplastic forming processes inside the strip or slab in more detail, and to develop fast simulation tools, semi-analytical model reduction approaches were developed. This enables a quantitative analysis of the induced lateral material flow and the occurring stress-redistributions inside the roll bite. By introducing a lateral material transfer parameter directly correlated to the centerline-curvature, an analytical relation could be derived for the bending moment, respectively for the external work, that has to be applied to eliminate the camber of the strip or slab. These analytical predictions, although based on rough simplifications, correspond quite satisfactorily with those attained by 3D-FE simulations.

Keywords: Hot Rolling, Slab, Wedge, Camber, Edger, Bulk Forming, Finite Elements, Analytical Models.

1. INTRODUCTION AND SURVEY

The hot rolling process can be considered as a key step within the production chain of high quality steel strip and plate material. To attain a more detailed insight into the elasto-viscoplastic forming phenomena (see e.g. Neto et al., 2008, Simo et al., 1998, Belytschko et al., 2002) during the rolling process (cf. Hosford et al., 2007), the application of customized on- and off-line models and tools is essential. For the prediction of 3D-effects during the roughing process of thick slabs, such as the lateral material flow and the influence of an edger, adequate 3D models are of utmost importance.

Rolled strip is ideally both straight (i.e. without camber) and left-right symmetric with respect to thickness over width (i.e. without wedge). Unfortunately, if a wedge within the slab is removed through swiveling of the rolls without further countermeasures, a camber will result, which - from a quality point of view – might be even worse than wedge. Modern, so called "camber free rolling systems" apply cameras to swivel roll sets in roughing or finishing mill stands to minimize the lateral curvature (camber) of the produced strip. Hence, all shape errors on the slab, i.e. initial camber or wedge are transferred into a "camber-free" wedge on the coil. This resulting wedge has to be accepted, if no additional actuator is employed.

Hence, the question arises, how to remove camber and wedge simultaneously. For a study of such questions, the development of fast reduced semi-analytical software-prototypes for industrial offline- and online applications is of particular interest. Purely analytical considerations regarding the prediction of the induced lateral material flow and the corresponding stress and strain re-distributions resulting from external lateral forces applied onto the slab outside the roll gap (e.g., by utilizing an edger) will be outlined in section 2. However, as some essential physical effects are not explicitly incorporated in this rather simple analytical model, it is primarily useful for qualitative considerations (e.g. sensitivity analyses). More refined semi-analytical 3D roll-gap modelling approaches, which are currently under development, will be valuable for precise quantitative predictions as well.

In section 3 of this study, the 3D-simulation of severely non-symmetric coupled flat hot rolling and edging processes is

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performed by utilizing the commercial FEM-Packages ©Abaqus Standard and Explicit. This enables the reliable prediction of camber formation (cf. Shiraishi et al., 1991, Knight et al., 2003, Montague et al., 2005, Nilsson, 1998) due to prescribed strip and slab wedge in hot rolling as well as of its suppression. Moreover, it leads to a deeper understanding of the underlying process details, which is a prerequisite for further process mechatronisation (model based design and model based control) targeting improved product quality. It enables the prediction of profile transfer, eigenstrains, residual stresses for highly asymmetric rolling scenarios for a single mill stand coupled with heavy sideguides and edgers. The developed enhanced models will also lead to an improvement in prediction quality for a wide variety of process parameters and support the optimization of production plants. Modelling and simulation have to be accompanied by validation and calibration with measured mill data.

2. ANALYTICAL INVESTIGATIONS

In this section the behaviour of a wedged slab running through one horizontal roll pass with aligned rolls is analysed (at least to some extent) analytically. Due to the wedge on the entry side and the alignment of the rolls, the material obtains different reductions on the operator side and on the drive side of the material. As a consequence, the side with higher reduction shows higher elongation. This results in a curvature of the material on the exit side and camber develops. The impact of an externally applied lateral force, e.g. resulting from an edger, would cause an asymmetric tension regime, which compensates the different elongations by inducing an additional lateral material flow. Therefore, the wedge can (at least in principle) be eliminated fully without formation of camber by choosing the correct lateral force-value.

In the following, the x-coordinate of the underlying global Cartesian coordinate system denotes the rolling direction, whereas y and z indicate the thickness and lateral directions of the strip or slab, respectively. A non-dimensional lateral coordinate over strip width w is introduced via

$$z = \frac{w}{2}\eta \quad \rightarrow \quad \eta \in [-1, +1] \ . \tag{1}$$

Within the frame of perturbation theory, the special case of plane strain (i.e. no lateral material flow) can be considered as "undisturbed" scenario of pure thickness reduction with logarithmic strain values

$$\varepsilon_{xx}^{(0)} = \left(-\varepsilon_{yy}^{(0)}\right) = \ln\left(\frac{H_C^{(In)}}{H_C^{(Out)}}\right) > 0 \ . \tag{2}$$

For simplicity, linear wedge-profiles are assumed here for the strip entry- and exit profiles (*In:* before roll-gap entry, *Out:* after roll-gap exit). $H_c^{(In)}, H_c^{(Out)}$ denote the thicknesses at the strip centerline.

$$H^{(In/Out)}(\eta) \cong H_C^{(In/Out)}\left[1 - \frac{W_{abs}^{(In/Out)}}{2H_C^{(In/Out)}}\eta\right] \ . \tag{3}$$

A generalization of (3) for linear wedges to arbitrary non-linear strip-entry profiles is straight forward and can be performed systematically by utilizing, for instance, an expansion in series of Legendre-polynomials $P_k(\eta)$.

By taking into account a small relative strip wedge change ΔW_{rel}, defined as the difference of the absolute strip wedge values, $W_{abs}^{(In)}, W_{abs}^{(Out)}$ divided by the respective nominal (C: Centreline) thickness values

$$\Delta W_{rel} \equiv \left(\frac{W_{abs}^{(Out)}}{H_C^{(Out)}} - \frac{W_{abs}^{(In)}}{H_C^{(In)}}\right) \quad with \quad \left\|\Delta W_{rel}\right\| << 1 \ , \tag{4}$$

the corresponding induced logarithmic (i.e., "true") plastic strains inside the strip or slab at the roll gap exit can approximately be assumed to be of the form (in lowest order of ΔW_{rel})

$$\varepsilon_{xx}(\eta) \cong \varepsilon_{xx}^{(0)} + (1-\zeta)\left[\eta\,\Delta W_{rel}/2\right] \tag{5}$$

$$\varepsilon_{yy}(\eta) \cong \varepsilon_{yy}^{(0)} - \left[\eta\,\Delta W_{rel}/2\right] \tag{6}$$

$$\varepsilon_{zz}(\eta) \cong \zeta\left[\eta\,\Delta W_{rel}/2\right] \ , \tag{7}$$

where the scalar "lateral material transfer factor" ζ is a measure of the magnitude of the lateral material flow involved. A value of $\zeta=0$ indicates the case of plane strain and zero lateral flow, whereas a value of $\zeta=1$ represents 100% lateral flow such that no longitudinal strain inhomogenities are induced across the strip's width.

Note that shear strains are neglected here. The plastic incompressibility constraint is fulfilled exactly for the logarithmic strain tensor components (5) - (7)

$$\underset{-1<=\eta<=1}{\forall} \left[\varepsilon_{xx}(\eta) + \varepsilon_{yy}(\eta) + \varepsilon_{zz}(\eta)\right] = 0 \ . \tag{8}$$

By neglecting higher orders in the relative strip wedge change ΔW_{rel}, the uniaxial equivalent plastic strain can be determined according to

$$\bar{\varepsilon}^{(p)}(\eta) \cong \frac{2}{\sqrt{3}}\varepsilon_{xx}^{(0)}\left[1 + \frac{1}{2}\eta\frac{\Delta W_{rel}}{\varepsilon_{xx}^{(0)}}\left(1 - \frac{\zeta}{2}\right)\right] \ . \tag{9}$$

Within the frame of Levy-Mises the deviatoric (i.e. trace-free) stress components σ'_{ij} of the Cauchy stress tensor are fully determined by the associated plastic flow rule. To calculate the stresses itself, two more conditions have to be taken into consideration, namely the lateral force equilibrium and the longitudinal stress boundary condition for prescribed mean front tension stress $\bar{\sigma}_F$. These two conditions enable the unique determination of the hydrostatic pressure p and of the Cauchy stresses, which read in lowest order of ΔW_{rel}

$$p(\eta) = \left[-\bar{\sigma}_F + \frac{k_f}{\sqrt{3}}\left(1 + \frac{\zeta}{2}\frac{\Delta W_{rel}}{\varepsilon_{xx}^{(0)}}\eta\right)\right] \tag{10}$$

$$\sigma_{xx}(\eta) = \left[\bar{\sigma}_F - \frac{k_f}{\sqrt{3}}\left(\frac{3\zeta}{4}\right)\frac{\Delta W_{rel}}{\varepsilon_{xx}^{(0)}}\eta\right] \tag{11}$$