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**Prediction EXEC-PapersOnLine 49-20 (2016) 238-243** *Prediction* **<b>of EXEC-PapersOnLine 49-20 (2016) 238-243 Prediction of the camebra formation**  $49-20$  (2010)  $230-243$ 

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

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side force acting on the strip induces a lateral material flow inside the roll gap, leading to stressredistributions such that the outgoing camber is drastically reduced. Systematic parameter studies equisibilities such that the outgoing callber is drastically reduced. Systematic parameter studies<br>performed so far by utilizing the commercial FEM-package  $_{\odot}$ 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 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. analysis of the mudeu fateral material flow and the occurring stress-redistributions listed the foll one.<br>By introducing a lateral material transfer parameter directly correlated to the centerline-curvature, an By introducing a fateral material transfer parameter unectly correlated to the centerine-curvature, and<br>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 and be depined to commate the caliber of the bending moment, respectively for the external work, although based on rough simplifications, correspond quite satisfactorily with those attained by 3D-FE simulations. **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 rough simplifications, correspond quite satisfactorily with those attained by 3D-FE simulations. **EXERCR:**<br> **VANDER SCRIPTED EXCREDUTED EXCREMENT INTERFERNATION INTERFERNATION (FIRSUM INTERFERNATION SUBSERVIER)<br>
<b>Production of camber formation, suppression**<br> **Production of camber Scripts and Production**, John (e-mails rough simplifications, correspond quite satisfactorily with those attained by 3D-FE simulations. (e-mail: larissa.aigner@voestalpine.com)

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

## 1. INTRODUCTION AND SURVEY 1. INTRODUCTION AND SURVEY 1. INTRODUCTION AND SURVEY 1. INTRODUCTION AND SURVEY

The hot rolling process can be considered as a key step within the not folling process can be considered as a key step whilm material. To attain a more detailed insight into the elastoviscoplastic forming phenomena (see e.g. Neto et al., 2008, Simo et al., 1998, Belytschko et al., 2002) during the rolling Simo et al., 1998, Belytschko et al., 2002) 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 and prediction of 3D effects dailing 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. The hot rolling process can be considered as a key step within the not folling process can be considered as a key step within  $\mu$  matterial. To attain a more detailed into the elasto-the elast viscoplastic forming phenomena (see e.g. Neto et al., 2008,  $\frac{1}{2000}$  et al., 2008,  $\frac{1}{2000}$  belief al., 2008,  $\frac{1}{2000}$  et al., 2009,  $\frac{1}{2000}$ broad et al., 1996, belyisched et al., 2002) during the folling  $\mu$ ustomized on- and on-ine models and tools is essential. For the prediction of  $3D$ -effects during the roughing process of of an edger, adequate 3D models are of utmost importance. the production chain of high quality steel strip and plate viscoplastic forming phenomena (see e.g. Neto et al., 2006,<br>Simo et al., 1009, Dalytechko et al., 2002) during the relling Simo et al., 1990, Belytschko et al., 2002) during the rolling 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. removed the removement with the respect to different solver with the rolls without wedge). Unfortunately, if a wedge within the slab is minear weage). Sincrealizery, in a weage within the state is<br>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 rolled "camber free rolling systems" apply cameras to swivel edition call the correlation of the produced strip. Hence, all the produced strip. Hence, all  $\epsilon$  is the product of the produced strip. Hence, all  $\epsilon$  is the product of the produced strip. Hence, all  $\epsilon$  is the product For see in reagaing or initially init stands to infinitive the lateral curvature (camber) of the produced strip. Hence, all relateral curvature (camber) of the produced strip. Hence, and<br>shape errors on the slab, i.e. initial camber or wedge are Rolled strip is ideally both straight (i.e. without camber) and  $R$  Rolled strip is ideally both strip is ideally both straight (i.e. without camber) and  $\alpha$ Rolled strip is ideally both straight (i.e. without callber) and<br>loft right symmetric with respect to thickness over width (i.e. without wedge). Unfortunately, if a wedge within the slab is left-right symmetric with respect to thickness over width (i.e. without wedge). Omortunately, if a wedge within the stab is removed unough swiveling of the folls without further called "camber free rolling systems" apply cameras to swivel point of view – might be even worse than wedge. Modern, so called called the folling systems apply called to swivel<br>roll sets in roughing or finishing mill stands to minimize the roll sets in roughing or finishing mill stands to minimize the<br>lateral aurusture (combar) of the produced strip. Hence, all without wedge). Unfortunately, if a wedge within the slab is removed through swiveling of the rolls without further shape errors on the slab, i.e. initial camber of wedge are

transferred into a "camber-free" wedge on the coil. This resulting wedge has to be accepted, if no additional actuator is employed. transferred into a "camber-free" wedge on the coil. This transferred into a "camber-free" wedge on the coil. This realisting we are to be a to transferred into a "camber-free" wedge on the coil. This resulting wedge has to be accepted, if no additional actuator

transferred into a "camber-free" wedge on the coil. This camber of the coil. This camber of the coil. This camb

Hence, the question arises, how to remove camber and wedge Frence, the question arises, how to remove cannoel and wedge<br>simultaneously. For a study of such questions, the development of fast reduced semi-analytical softwareprototypes for industrial offline- and online applications is of predicty per term material crimine and emine approaches to experience particular interest. The regional constructions 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 enternal rateal rores approaches are one to state the roll gap (e.g., by utilizing an edger) will be outlined in section 2. However, as some essential physical effects are not explicitly proverty, as some essential priysical errors are not expressed for the constant proporated in this rather simple analytical model, it is more primarily useful for qualitative considerations (e.g. sensitivity primarily useful for qualitative considerations (e.g. primality assemble constantine constantine (e.g. semi-trivity analytical 3D roll-gap development, which is the valuable for precise and the value of problem approaches, which are currently under development, will be valuable for precise quantitative predictions as well.  $\mathbf{H}$  and  $\mathbf{H}$  are move can be removed camber and we define the remove camber and we define  $\mathbf{H}$ Frence, the question arises, now to remove cannot and wedge  $d_{\text{min}}$  a subsetted semi-analytical social social society. protophiem of last request semi-analytical softwareprototypes for muustrial offline- and online applications is of<br>porticular interest. Burgly applytical considerations regarding  $t_{\text{in}}$  the induced lateral material flow and the induced lateral flow and  $\mu$  is a stress and stress and stress and stress and stress results from  $\mu$ . external lateral forces applied onto the slab outside the roll corresponding stress and strain re-distributions resulting from  $\alpha$  can be utilizing an edger) will be outlined in section 2. However, as some essential physical effects are not explicitly gap (e.g., by utilizing an edger) will be outlined in section 2. incorporated in this rather simple analytical model, it is However, as some essential physical effects are not explicitly primarily useful for qualitative considerations (e.g. sensitivity incorporated in this rather simple analytical model, it is  $\mu$  many useful for quantative considerations (e.g. sensitivity  $\frac{1}{100}$  analyses). More refined semi-analytical 3D fon-gap moderning approaches, which are currently under<br>development will be valuable for precise quantitative  $\alpha$ evelopment, will simultaneously. For a study of such questions, the particular interest. Purely analytical considerations regarding primarily useful for qualitative considerations (e.g. sensitivity development, will be valuable for precise quantitative predictions as well.

In section 3 of this study, the 3D-simulation of severely nonsymmetric coupled flat hot rolling and edging processes is In section 3 of the 3D-simulation of severely non- $\frac{1}{2}$  in section 5 of this study, the 5D-simulation of severely nonsymmetric coupled hat not rolling and edging processes is 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 *<sup>w</sup>* 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

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

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).  $H_c^{(ln)}$ ,  $H_c^{(Out)}$  denote the thicknesses at the strip centerline.

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

A generalization of (3) for linear wedges to arbitrary nonlinear 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  $\Delta W_{rel}$ , defined as the difference of the absolute strip wedge values,  $W_{abs}^{(ln)}$ ,  $W_{abs}^{(Out)}$  divided by the respective nominal (C: Centreline) thickness values

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

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  $\Delta W_{rel}$ )

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

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

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

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)

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

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

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

Within the frame of Levy-Mises the deviatoric (i.e. tracefree) stress components  $\sigma'_{ij}$  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  $\bar{\sigma}_r$ . These two conditions enable the unique determination of the hydrostatic pressure p and of the Cauchy stresses, which read in lowest order of ∆W<sub>rel</sub>

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

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

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