IMPLEMENTATION OF PROCESS SETUP CALCULATIONS AND AUTOMATION CONTROLS IN FINITE ELEMENT ANALYSIS OF HOT STEEL STRIP ROLLING*

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Abstract

Finite element method (FEM) is widely used to model the hot strip rolling process. Flatness defects e.g. front-end bending in multipass hot strip rolling is studied by authors using a finite element (FE) model with interactively operating automated controlling logic (ACL) [1]. However, industrial corresponding grade of accuracy in strip thickness subsequent to the rolling pass is not easily accessible in FE-model without separate calculation of significant rolling parameters and integrated roll gap control. In order to study flatness defects and optimize pass schedules the controlling and physics of the FE-model must correspond to the industrial process. For this need the automated controlling logic is upgraded by setup calculations to predicting roll force and work roll flattening. These predictions are utilized in setup positioning of a work rolls. Reliable setup calculation enables smooth multi stand rolling process without significant additional adjustment of roll gap clearance. State of art rolling technology requires above-mentioned setup controlling for the FE simulations to simulate different pass schedules without time consuming preparations. Operational setup calculations together with automated controlling logic of hot strip rolling enable simulation of new pass schedules and efficient problem solving.

Keywords: Hot strip rolling; Roll gap control; Rolling automation; Roll flattening

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1 INTRODUCTION

Especially the investigation of the front-end bending phenomenon requires pre-calculated setup values for roll gap positioning at strip entry. The most critical point of time for front-end bending formation is the strip entry into the roll bite. The combination of entry angle, temperature gradient in a strip, contact condition differences in a roll bite and roll gap geometry i.e. shape factor jointly define the formation of front-end bending. The importance of setup calculations for roll force is emphasized in slow roll gap adjustment e.g. screwed control. Thus, the front-end of a steel strip may be rolled with incorrect gap value. Incorrect prediction for rolling force or roll flattening leads to misplaced roll gap clearance requiring additional adjustment of roll gap causing changed roll gap geometry and thickness deviations. These defects must be revised in the next rolling passes making process more unstable. In addition, roll force and work roll flattening need to be considered in roll gap adjustment of the FE-model to achieve desired exit thickness of the strip.
In our preliminary simulations of front-end bending formation at hot strip mill, it has been found that by redefining the pass schedule i.e. roll gap the direction of front-end bending can be changed [1]. This behaviour is published in several researches on roughing or plate rolling processes [2, 3, 4]. Shape factor is generally used index in this connection. It simply describes a ratio of contact length and mean strip thickness in a roll bite. Shape factor reacts significantly to geometrical changes in the roll gap and thus, accurate setup values of FE-model are demanded. Implementation of ACL into FE-model of hot strip rolling process is published by authors in [1] and preliminary calculations for predicting roll force in [5]. Now ACL is expanded considering dynamic effects of rolling process i.e. strip inertia. If dynamic effect of strip inertia is neglected, it leads to defective strip tensioning by loopers and thus need to be considered.
In order to design practicable pass schedules based on FE simulations, the restrictions of hot strip mill must be known. Each rolling stand has limitations regarding roll force and torque. This sets boundary values for pass schedule designing and thus reliable prediction of roll force and torque is required. So, the following setup calculations are needed for two applications: to calculate setup values for the passes in FE-model considering roll flattening as well as to define loads of the redefined pass schedules. Without ACL, the FE-model would be too idealistic.

2 FEM MODEL

The mechanics and physics of the 2D FE-model of six stand hot strip mill is based on corresponding author's FE-model introduced in [1, 6]. The rolling model utilizes non-linear facilities of a dynamic temperature-displacement analysis with an Explicit solver of software package Abaqus™. A finely discretized geometry of a steel strip is meshed with plane strain CPE4RT thermally coupled quadrilateral elements with enhanced hourglass control. Heat transfer in the rolling process occurs by convection, radiation and thermal conductance. Magnitudes of these variables are applied as experimentally determined coefficients in [7].
Plastic deformation resistance of a steel strip with respect to the temperature and strain rate is defined experimentally by thermo-mechanical simulator Gleeble™ 3800 to get a reliable response of the material behavior in the FE simulation and setup calculation. A fitting model depicting hot material plastic mechanical response, called Hensel-Spittel (H-S) equation is fitted into experimental flow curves to describe deformation resistance in the setup calculations and FEM simulations (Figure 1). H-S fitting is depicted by authors in [1, 6]. Flow stress k_f is

calculated by (Equation 1) and fitting parameters are shown in (Table 1).

$$k_f = a_1 \cdot \epsilon^{a_2} \cdot exp(a_5\epsilon) \cdot \dot{\epsilon}^{a_3} \cdot exp(-a_4T) \cdot (1+\epsilon)^{a_6 \cdot T} \cdot \dot{\epsilon}^{a_7 \cdot T} \cdot T^{a_8} \cdot exp\left(\frac{a_9}{\epsilon}\right) \quad (1)$$

where k_f is flow stress, ϵ is strain, $\dot{\epsilon}$ is strain rate, T is temperature in °C and a_i are fitting parameters.

Table 1. Fitting parameters for the H-S equation

a_1	3716.958
a_2	0.406549
a_3	-0.12841
a_4	0.003224
a_5	-0.55799
a_6	-0.000214
a_7	0.0002406
a_8	0.06628
a_9	-1E-7

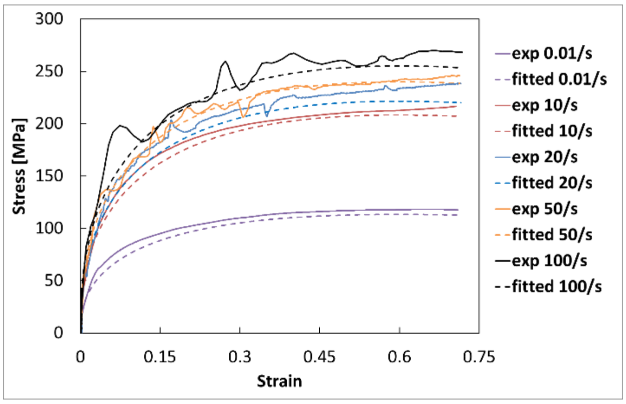

Figure 1. Experimental and fitted Hensel-Spittel stress-strain curves at 900 °C

3 TANDEM MILL AUTOMATION

All temperature dependent material properties are defined by chemical composition of the selected steel grade using Inter Dendritic Solidification (IDS) analysis package [8]. Material flow, strip tension, rolling speed and roll gap clearance are controlled by ACL in the FE-model. ACL is implemented numerically using a VUAMP-subroutine to control looper moments as well as work roll positioning and rotation velocity in Abaqus (Figure 3). Operating principle of the ACL is represented by corresponding author in [1]. Load state *q(x)* of a looper tension (Figure 2) in statically equilibrium system is shown in (Equation 2). This considers required torque to bend the strip, nullify the effect of gravity and reach the specified lengthwise tension in the strip.

$$q(x) = \int\int\int\int -EIv \quad (2)$$
$$= F1_y\langle x\rangle^{-1} - M_y\langle x\rangle^{-2} - N_y\langle x-\frac{L}{2}\rangle^{-1} + F2_y\langle x-L\rangle^{-1} + M_y\langle x-L\rangle^{-2}$$

Required force N_y (Equation 3) between the looper roll and the strip can be solved from *q(x)* and required torque to bend the strip in roll bite by (Equation 4). Strip is

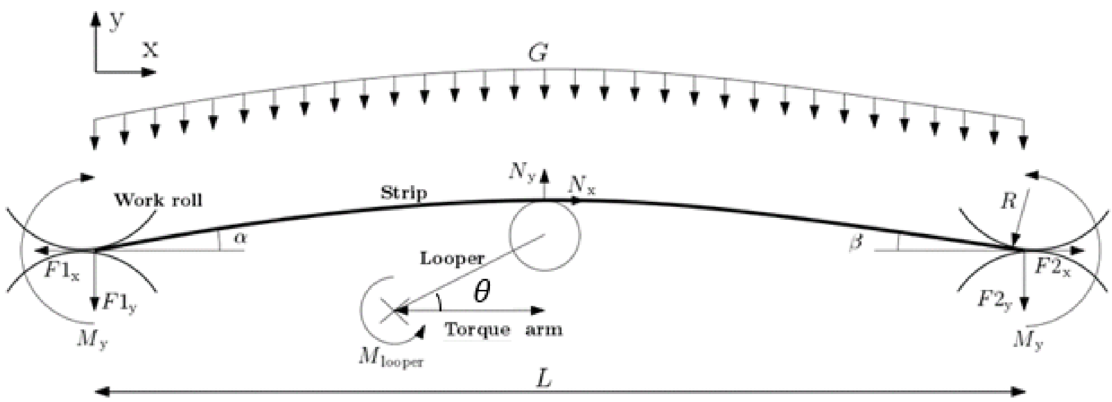

Figure 2. Schematic drawing of strip tensioning

assumed to

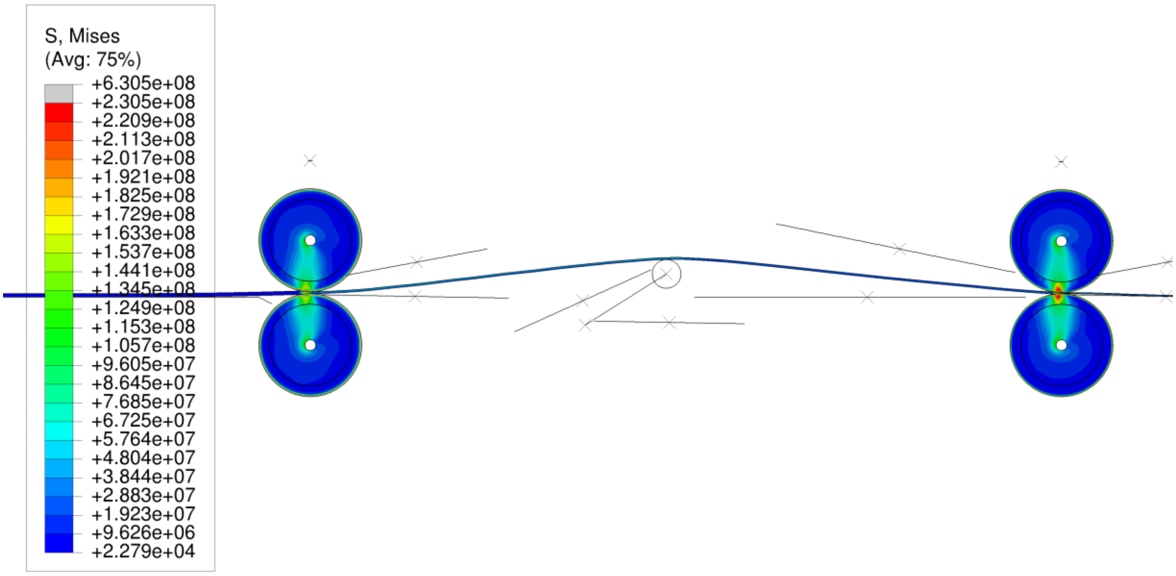

Figure 3. First and second rolling stands of FE-model

behave as ideal plastic material during strip bending in ACL calculations (Figure 4).

$$N_y = \frac{M_y 8}{L}, \quad M_y = \frac{\sigma_y I_z}{H} \quad (3,4)$$

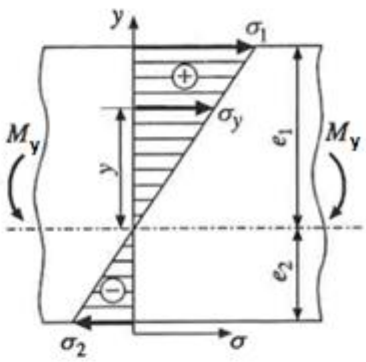

Figure 4. Bending torque in a strip

The ACL is extended to consider dynamic effects of the strip inertia due to diversion caused by looper tension, Sansal K. Yildiz used simplified Newton's law of motion to define strip inertia. The strip inertia M_{strip} can be written as follows in (Equation 5) [9].

$$M_{strip} = \frac{1}{30} L^2 hw\rho l \cos\theta \, \ddot{\theta} \quad (5)$$

where *h* is strip gauge, *w* is strip width, *ρ* strip density, *l* is looper arm length and *θ* is rotation of looper arm.

3.1 Roll force calculation

Roll force is calculated by Sims equation (Equation 6) of specific roll load [10]. Sims equation uses von Kármán's equation of equilibrium and plastic-deformation derived by Orowan [11].

$$P = R'k\left[\frac{\pi}{2}\sqrt{\frac{h}{R'}}\tan^{-1}\sqrt{\frac{r}{r-1}} - \frac{\pi\alpha}{4} - \log_e\frac{Y}{h} + \frac{1}{2}\log_e\frac{H}{h}\right] \quad (6)$$

where: R' is deformed work roll radius calculated by Hitchcock's equation (Equation 7), k is mean flow stress of the material in plane strain compression, h is exit thickness of strip, H is entry thickness of strip, r is fractional reduction in pass, α is angle of contact between strip and work roll at the plane of entry and Y is neutral thickness of the strip [12].

$$R' = R\left[1 + \frac{16 \cdot (1 - \upsilon^2)}{\pi \cdot E \cdot w \cdot \Delta h} \cdot P\right] \quad (7)$$

where R is undeformed roll radius, υ is Poisson's constant, E is Young's modulus of the work roll and Δh is draft.

H-S equation is fitted on uniaxial compression tests and thus must be transformed into following form $\frac{2}{\sqrt{3}} k_f$ to respond plane strain conditions in rolling process referring to the theory of Huber-Mises and used by Orowan [11]. To get an approximation of mean flow stress in certain roll bite, the averaged flow stress of entry and exit stress states of H-S equation are calculated and combined into mean flow stress by using following equation (Equation 8). The exit stress state is emphasized in the averaging.

$$k = \frac{2}{\sqrt{3}} \cdot \frac{k_{f\,entry} + 2 \cdot k_{f\,exit}}{3} \quad (8)$$

Accumulation of plastic strain ε is calculated for every rolling stand. Plastic strain gained on previous rolling passes is used to define entry flow stress where the strain gained at the current stand is added on exit flow stress. Stress state is assumed to remain unchanged after the cumulative strain exceeds 0.7 strain. Strain rate is calculated by (Equation 9) as Sims defined in [10].

$$\dot{\epsilon} = \frac{2 \cdot V_r \cdot \sin\beta}{h + 2 \cdot R' \cdot (1 - \cos\beta)} \quad (9)$$

where V_r is peripherical speed of work roll and β is neutral angle in the roll bite (Equation 10). Y is neutral thickness of the strip at the plane of intersection (Equation 11).

$$\beta = \sin^{-1}\left[\frac{1}{2} \cdot \left(\sin\alpha - \frac{1 - \cos\alpha}{\mu}\right)\right] \quad (10)$$

$$Y = h + 2 \cdot R' \cdot (1 - \cos(\beta)) \quad (11)$$

where μ is friction coefficient and α is entry angle (Equation 12).

$$\alpha = \sqrt{\frac{Hr}{R}} \quad (12)$$

3.2 Forward slip

Forward slip is a significant parameter in rolling-speed control. For the setup calculation the first parameter to calculate is peripherical velocity of a work roll. In multi stand rolling process the meaning of accurate setup velocities is emphasized due to material flow control. Equation for forward slip f_i and strip exit velocity V_{exit} as well as for peripherical V_r and angular V_ω velocities of work roll are defined by (Equations 13 - 16) respectively [13].

$$f_i = \frac{Y}{h} \cdot \cos\beta \quad (13)$$

$$V_{exit} = V_0 \cdot \frac{H}{h} \ (plane\ strain) \quad (14)$$

$$V_r = \frac{V_{exit}}{f_i + 1}, \quad V_\omega = \frac{V_{exit}}{(f_i + 1) \cdot R} \quad (15, 16)$$

3.3 Heat generation and cooling of strip

Heat generation within a strip during hot rolling is acquired by deformation of the strip. Frictional effects and metallurgical changes occurring in the strip are not considered in setup calculation. In the FE-model adiabatic process and frictional heat generation are taken into account. The theoretical energy of deformation per unit volume is $k \ln\left(\frac{1}{1-r}\right)$ referring William L. Roberts in [14], r is reduction. Heat generated by plastic deformation is then as shown in (Equation 17).

$$\Delta T = \frac{k}{\rho c} \cdot \ln\left(\frac{1}{1-r}\right) \quad (17)$$

During six passes of hot strip rolling process heat is lost by direct conduction to work rolls, radiation, air cooling and water cooling. These effects cool the strip surface and the inner of the strip is cooled by heat conduction within the strip. In setup calculation the heat conductance between the strip and work roll is calculated with aircooling and radiation to ambient. The combined emissivity factor E_{comb} for air cooling and radiation and effective heat transfer coefficient H_c in the contact of strip-work roll is applied by experimental measurements in [7]. Temperature drop in the strip due to conductivity is as in (Equation 18).

$$T_{cond} = 60 \cdot H_c \cdot \sqrt{\frac{r}{HR}} \cdot \left(T_{strip} - T_{roll}\right) \cdot [(1-r) \cdot \pi\rho c N]^{-1} \quad (18)$$

where T_{strip} is strip temperature, T_{roll} is work roll temperature and N is rolling speed (*rev/min*). The effect of air cooling and radiation to ambient are considered using combined emissivity factor E_S. Strip temperature loss after time t is then given by (Equation 19) [14].

$$T_{rad+air} = T_0[1 + 6 \cdot SE_{comb}T_o^3 t(\rho ch)^{-1}]^{-\frac{1}{3}} \quad (19)$$

3.4 Work roll indentation

Actual work roll indentation due to contact pressure is required in setup calculations of rolling automation to correct roll gap clearance. As a mechanical constraint formulation, the penalty contact method is used in the FE-model. Penalty contact demands overclosure of contact surfaces to generate contact. Proportioned contact is managed by short springs between contact nodes and the stiffness of these springs. This overclosure is not considered in this paper and will be discussed in further studies. Therefore, the exit thickness of the rolled strip is always slightly thicker than issued in the pass schedule though the work roll indentation is considered.

Sims showed in [10] that normal roll pressure s^+ on contact area can be defined with respect to angular coordinate commencing at the plane of exit till plane of entry by (Equation 20).

$$s^+ = \frac{k}{\frac{\pi}{4}\ln\left(\frac{y}{h}\right) + \frac{\pi}{4} + \sqrt{\frac{R'}{h}} \cdot \operatorname{atan}\left(\frac{R'}{h}\right) \cdot \beta} \quad (20)$$

where

$$y = h + R' \cdot \beta^2 \quad (21)$$

Substituting normal pressure into contact between cylinder and plate according to Hertz contact theory [15] the indentation of work roll surface can be presented. Radius of contact area $l_{contact}$ is calculated by (Equation 22).

$$l_{contact} = \frac{\pi \cdot s^+ \cdot R_{eff}}{2 \cdot E_{eff}} \quad (22)$$

where

$$R_{eff} = \frac{1}{\frac{1}{R'} + \frac{1}{R_{strip}}} \quad (23)$$

$$E_{eff} = \frac{1}{\frac{1-\nu^2}{E_{roll}} + \frac{1-\nu^2}{E_{strip}}} \quad (24)$$

where R_{eff} and E_{eff} are effective radius and elastic modulus for the roll-strip contact, respectively, R_{strip} is plate surface radius (defined as infinitely large radius), E_{roll} and E_{strip} are elastic modules of work roll and strip, respectively. Displacement for the work roll surface may be written as in (Equation 25).

$$u_z(z) = \frac{\pi \cdot s^+}{4 \cdot E_{eff} \cdot l_{contact}} \cdot \left(2 \cdot {l_{contact}}^2 - z^2\right) \quad (25)$$

where $z = 0$ is work roll surface displacement i.e. indentation.

4 RESULTS AND DISCUSSION

Verification of the implemented setup calculation of roll force prediction was carried out by comparing forces to measured roll forces of six stands hot strip rolling mill. Measured roll forces were gathered after the peak force caused by strip entry. Pass schedules were randomly selected, and the same H-S fitting was used for all simulations. Final thicknesses of simulated pass schedules were between 2.2 mm and 12.0 mm. In the (Figure 5) is shown the comparison between measured and setup calculated roll forces.

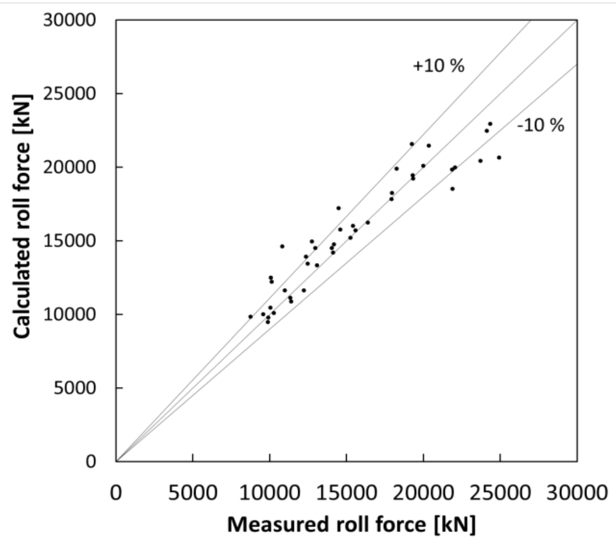

Figure 5. Comparison between calculated and measured roll forces

Good correspondence between the roll forces obtained from the setup calculations and the measured values was obtained, as shown in (Figure 5). First passes with high roll forces are slightly lower than predicted. This is due to relatively low strain rates at these passes whereas H-S fitting is emphasized by high strain rates from experimental test results.

Predicted roll forces are used for all six rolling stands in FE-model simulations to predict roll gap clearance. Work roll indentation and elongation of individual rolling stands are depended on the roll force. After the strip head has passed the roll bite, the ACL takes over the control from setup calculation and starts use sensor data from FE-model and thus corrects the clearance of roll gap if it is misplaced after setup positioning. Predicted work roll (WR) positions for the first and second rolling stands in FE-model are depicted in (Figures 6 and 7), respectively. Positions are calculated with respect to rolling forces of setup calculations. Corrected roll bite clearances are also shown in these figures. Only minor corrections are needed in roll gap clearance, which suggests reliable roll force prediction and the same deformation resistance in both models. This verifies setup calculations to be a good prediction for the different pass schedule simulations by the FE-model.

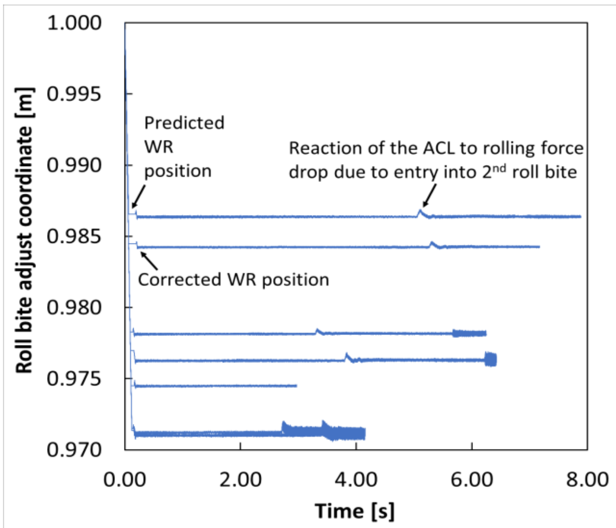

Figure 6. Predicted and corrected WR positions in FE-model at 1st rolling stand

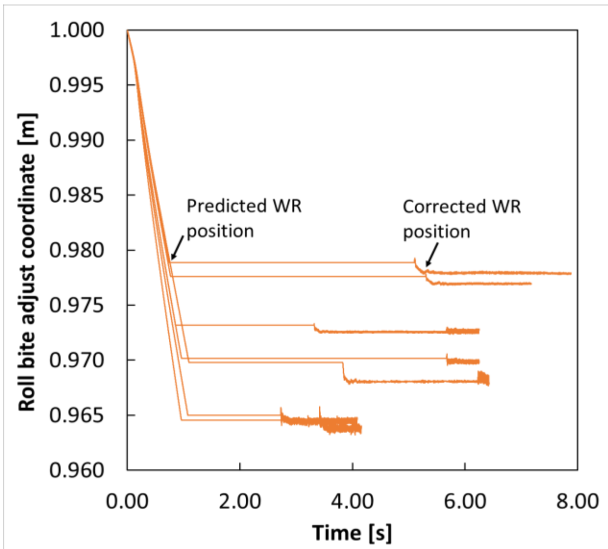

Figure 7. Predicted and corrected WR positions in FE-model at 2nd rolling stand

5 CONCLUSION

The FE-model and the ACL of the hot strip rolling mill are upgraded to predict WR flattening and roll force for any pass schedules. This enables more accurate and stable FEM simulation, simultaneously decreasing the need of ACL adjustment after strip entry. The roll forces for any hot strip rolling pass schedules can be predicted with very good accuracy making in-process controlling smoother. Thus, the roll gap clearance is set at the required exit thickness of the strip by setup positioning and only fine control is needed after the rolling has started. In that case reduction is not changed significantly and major chances in rolling speed and looper tensioning is not needed. This responds the real rolling process and the strip entry into roll bite can be simulated more precisely. In the upcoming studies the flow stress prediction by H-S equation will be divided in strain rate ranges improving the response of lower strain rate flow stresses. As a computational issue the overclosure of contact surfaces in penalty contact method will be considered in further studies.

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