

Profile Contour and Flatness Control Model for Hot Strip Rolling

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Abstract. A full Profile Contour and Flatness Control (PCFC) model prototype has been developed for hot finishing mills. This model prototype accounts for several physical based sub-models calculating the different contributions to the roll gap profile and allows for offline predictions in both preset and recalculation modes. To evaluate the PCFC model developed, an exhaustive comparison analysis between its calculations, the ones coming from the plant model and measures at the finishing mill exit has been carried out. An industrial mill database composed of different rolling campaign types was applied for this purpose and both (i) strip crown and flatness indicators as well as (ii) full strip profiles results have been used for the comparisons. Encouraging results were obtained from this performance assessment since the PCFC model developed leads to similar behavior compared to the existing plant's model (from an industrial supplier). As a result, the PCFC model developed shows high potential for online implementation in hot strip mills.

Introduction

In hot rolling, Profile Contour and Flatness Control (PCFC) models are crucial not only to respect the tolerance of the final strip crown and flatness but also for rolling stability to maintain a good strip shape in inter-stands to avoid cobbles, rolling incidents and increase mill productivity. These PCFC models consist of complex systems that must account for (i) any mechanical actuator applied on the finishing mill stands, (ii) several sub-models to calculate the different contributions to the roll gap profile and strip shape, (iii) preset strategies as well as (iv) adaptation contribution [1]. In this way, the performance of those models depends on the actuators technologies applied on the rolls and finishing stands, like work-roll bending [2], continuous variable crown [3,4], smart crown [5] or work roll shifting [6], but also on the quality itself of the PCFC model that presets these actuators to reach targeted exit strip crown and flatness from customer requirements [7].

Most part of the PCFC systems currently deployed on hot strip mills are based on physical sub-models to predict roll gap profile and strip shape at several hot finishing stands [8–11]. More recent developments on PCFC systems tend to be focused on applying machine learning (ML) approaches. However, part of these ML approaches may struggle with accuracy and reliability as they usually rely only on data driven learning and fail to incorporate process specific knowledge [12]. To address this type of limitation, physics-informed ML models integrating engineering insights have also been proposed by some authors by deriving process knowledge through finite element analysis [12], mechanical principles [13] or physical based formulations [14,15] to enhance predictions and ensure better consistency with real-world process dynamics. However, a large number of these ML approaches are mainly focused on the prediction of the hot-rolled strip crown for the last stand by often using theoretical strip crown [16,17] or roll gap [18,19] values of the previous stands as initial input data. Nevertheless, a full PCFC system must predict roll gap contribution and consequent strip crown not only for the last stand but for all the finishing stands in order to preset mill actuators accordingly. It must be kept in mind that, for industrial online application, a PCFC system must be designed to determine effective mill actuators preset simultaneously for all the finishing stands and at every strip to be rolled by delivering fast calculations.

Still, it was demonstrated that ML model approaches may outperform the physical based models for hot strip mills running low number of different strip grades, limited strip width ranges or specific rolling schedules [15,20]. In fact, several studies have proved that ML approaches have significant potential in this field but there are still problems such as unstable high data quality and data standardization, poor adaptability to the actual production environment with continuous working conditions changes, insufficient model interpretability and decision-making trust for process engineers that must be addressed to make possible a full industrial application [21]. Then, some progress still needs to be done to have this type of solutions running online for real-time control of the rolling process over all the hot finishing stands and for a large production mix.

From an industrial point of view, commercial PCFC models running today on hot strip mills are essentially black-box supplier's solutions not allowing for tailor-made modifications. On top of that, these supplier's solutions are sometimes showing limitations on delivering reliable mill actuators preset particularly for most recent strip grades.

Thus, the main goal of this work is to develop an effective PCFC model prototype for hot finishing mills i) based on physical models knowledge and ii) that will enable to anticipate tighter tolerances in strip flatness and profile for 3rd generation Advanced High Strength Steels (AHSS) and especially, for electrical steel grades that require very uniform and flat profiles along the coils. A first performance assessment of this PCFC model prototype is also addressed here by using industrial data coming from a hot strip mill with 7 finishing stands (F1-F7), all equipped with bending and shifting actuators as well as continuous variable crown (CVC) rolls.

PCFC Model Description

The PCFC model developed allows for fast computations for an entire rolling campaign (≈ 0.2 sec per strip) and for 2 simulation modes which rely on different applications, for instance, recalculation and prospection. The recalculation mode is used to predict strip crown and flatness by giving mill actuators values as input data for all the finishing stands, while the prospection mode determines the mill actuators data set for each stand that would lead to a desired exit strip crown and flatness targets, at the exit of the finishing mill, by minimizing rolling instabilities on the inter-stands. Several sub-models calculating the different contributions to the roll gap profile, namely, (i) work-roll and backup roll wear, (ii) work-roll thermal crown, (iii) strip profile and (iv) stand models are included in the PCFC model prototype (Figure 1).

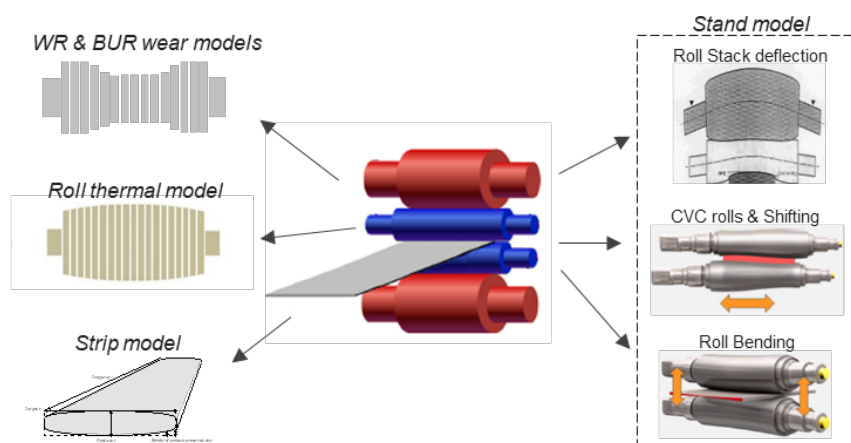


Fig. 1. Different models needed to calculate strip crown and flatness shape at each hot finishing mill stand.

Stand model.

The stand model corresponds to a semi-analytical formulation that allows for reliable work-roll deformation calculations by computing the equilibrium state of a vertical stack of rolls [22]. This model depends on initial strip shape, rolls geometry (variable profile like CVC or smart crown, chamfers, necks), strip and roll material properties, mill actuators as well as bending and rolling

forces. Its modelling is based on the axial rolls' discretization for half of the stand by using the following theoretical formulations [23]:

- Timoshenko beam theory for calculation of roll bending
- Hertz contact theory for arc length contact calculation
- Hitchcock theory for determining the longitudinal distribution of the rolling force over the roll-bite
- Boussinesq theory and Berger analytical solution to calculate roll flattening due to work-roll / strip or backup roll / work-roll contacts

A complete stand model calculation is launched at every new strip and then, this calculation is linearized around the working point of the strip by the following equation,

$$b_c = M^{\text{Lam}} \cdot F^{\text{Lam}} + M^{\text{Act}} \cdot F^{\text{Act}} + I^{\text{CT}} \cdot b_v^{\text{CT}} + I^{\text{CA}} \cdot b_v^{\text{CA}} + T \quad (1)$$

where b_c stands for the deformed roll gap profile at each contact node between strip and work-roll, F^{Lam} is a vector describing the rolling force distribution, F^{Act} is the vector containing the values of all mechanical actuators equipping the stand while b_v^{CT} and b_v^{CA} are vectors containing the off-load crown distribution at each node (grinding, wear and thermal crown contributions) for the work and backup rolls, respectively. In addition, I , T , M^{Lam} and M^{Act} are tensors depending on the number of strip nodes and/or stand actuators.

This linearization approach is needed to enable the coupling of the stand model with the strip model, however, it is also needed to know the sensitivity of the on-load crown to the off-load work-roll crown distribution. Therefore, the initial linearization given by Eq. (1) is thus adapted to,

$$b_c = M^{\text{Lam}} \cdot F^{\text{Lam}} + M^{\text{Act}} \cdot F^{\text{Act}} + M^{\text{vidT}} \cdot B_{va} + T \quad (2)$$

where, M^{vidT} is a tensor for the off-load work-roll crown contribution and B_{va} corresponds to the theoretical off-load crown adaptation amplitude considering the full work-roll barrel length. This linearized equation is then used along with a scalar strip model formulated to determine strip crown and flatness values at the 3 usual positions from the strip edge (25, 40 and 100 mm from edge). In this scalar approach, the effect of the rolling force heterogeneity over the strip width is neglected. Although the strip model is defined in a scalar approach, full strip crown and flatness profiles are anyway obtained through a polynomial extrapolation between the strip centre, the 3 crown indicators positions (C25, C40 and C100) and extreme strip edge.

Strip model.

The strip model developed to run the PCFC calculations consists of a scalar formulation which can be written as [24],

$$\frac{b}{h} = \frac{b_c}{h} + \eta(\varepsilon - fla) \quad (3)$$

with,

$$\varepsilon = \frac{B}{H} + FLA - \frac{b_c}{h} \quad (4)$$

and where, b and B stand respectively for exit and entry strip crown, fla and FLA stand respectively for exit and entry flatness, h and H correspond respectively to exit and entry thickness at strip center, b_c is the roll bite exit crown in affinity with entry strip crown, ε is the general deformation and η is the crown heredity coefficient which depends on the strip grade features. In this formulation, the exit flatness (fla) is defined as,

$$fla = \xi \varepsilon \quad (5)$$

where parameter ξ is a coefficient of sensitivity to flatness.

In order to link both strip and stand models, Eq. (2) must be simplified to assume a scalar form as well. This equation is then re-written in a scalar way as,

$$\frac{b_c}{h} = \frac{\varphi + \theta + \beta}{h} + \frac{T}{h} = \alpha + \frac{T}{h} \quad (6)$$

and then, stand model given by Eq. (6) and strip model given by Eq. (3) can be coupled as

$$\frac{b}{h} = \alpha + \frac{T}{h} + \eta(\varepsilon - fla) \quad (7)$$

where the term α is commonly called as intrinsic on-load crown ratio. By using this coupled equation, strip crown and flatness calculations are done at the 3 common crown indicator positions (C25, C40 and C100, which correspond to strip crown calculations respectively at 25, 40 and 100 mm from strip edge). As a result, this strip model accounts for 6 tuning coefficients to adjust the flatness sensitivity coefficient ξ ,

$$\xi_i = A_i \left(\frac{w}{h}\right)^{B_i}, \text{ with } i=1 \text{ to } 3 \quad (8)$$

where, w is the strip width, index $i = 1$ to 3 stands respectively for the crown indicator positions C25, C40 and C100 and both A_i and B_i are the strip model tuning parameters for each one of these indicator positions. Although this strip model is defined in a scalar mode, full strip crown and flatness profiles are obtained through a polynomial extrapolation between the strip center, the 3 crown indicators positions (C25, C40 and C100) and the extreme strip edge.

Roll thermal model.

The roll thermal crown model applied is a classic finite difference axisymmetric (r, z) model to calculate 2D roll temperature distribution based on averaged heat transfer over the roll circumference. This $\frac{1}{2}$ axisymmetric thermal model calculates an input heat flux (φ) based on a semi-empiric function which accounts for the roll-bite and cooling thermal exchanges over the roll surface. This model considers refined meshing over the radial direction and includes roll necks modelling as shown in Figure 2. On top of that, this thermal model also accounts for work-roll shifting and different thermal properties for roll core and shell.

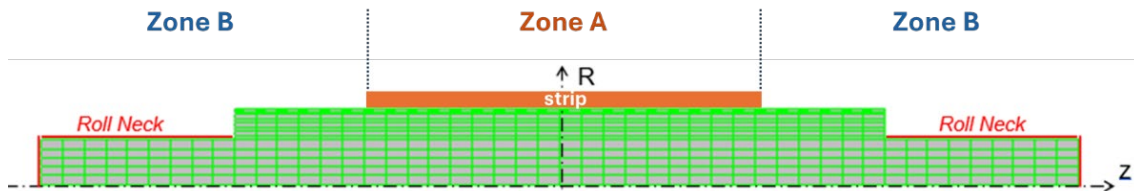


Fig. 2. One half work-roll mesh of PCFC's thermal model.

The heat exchanges along the roll barrel length are defined considering 2 distinct zones (see Figure 2), a zone A in direct contact with the strip and a zone B with no contact with the strip. The heat flux Φ for roll section in contact with the strip (zone A) is calculated by,

$$\Phi = H_{strip} \sqrt{l_{rb} v_R} (T_{strip} - T) + 2\pi R. H_{cool}^A \sqrt{v_R} (T - T_{cool}) \quad (9)$$

while the heat flux Φ for roll sections without strip contact (zone B) is calculated as,

$$\Phi = 2\pi R \cdot H_{cool}^B (T - T_{cool}) \quad (10)$$

where L_{rb} is the roll-bite contact length, H_{strip} is the roll-bite heat coefficient, v_r and R are the roll speed and roll radius, H_{cool}^A and H_{cool}^B are the coolant heat coefficients for zones A and B and, T_{cool} and T_{strip} are respectively the coolant and strip temperatures. From this formulation, heat flux dissipated by friction on roll-bite is neglected. However, higher roll-bite contact length or roll speed leads automatically to increased entry heat flux.

The roll thermal crown is calculated in this model by considering plane stress assumption [25],

$$u_R = \frac{2\alpha_{Roll}}{R} \int_0^R r \cdot \Delta T(r) \cdot \partial r \quad (11)$$

where u_R is the roll radial displacement due to thermal expansion, α_{Roll} is the roll thermal dilatation coefficient and ΔT is the local roll temperature variation from its initial temperature.

Work-roll wear model.

Roll wear phenomenon may involve simultaneously several mechanisms like abrasion, adhesion, chemical degradation, thermal and mechanical fatigue. The individual characterization and quantification of these mechanisms still remains very difficult, and so, most part of the wear models consist of contact-mechanic based equations assuming simplified relations between both material and process parameters [26]. The wear model adopted in the PCFC model prototype is also a contact-mechanic based equation. This roll wear equation is derived from Archard principles which stipulate that wear (volume loss) is proportional to the normal force by the sliding length [27]. This work-roll wear equation is based on a slicing method by equally dividing the work-roll in a certain number of slices over the roll barrel direction and can be defined as,

$$W_{WR} = k \frac{F \cdot L}{w} [1 + ax^n] \quad (12)$$

where, W_{WR} is the work-roll wear for one strip of the rolling campaign, F is the rolling force, w is the strip width, L is the rolling length, k is a wear factor tuning coefficient, a is a tuning coefficient of preferential wear at the edges of the roll wear profile, n is an exponent coefficient and x is the relative position along the strip width. Both k and a tuning coefficients can be defined as function of the finishing stand, work-roll type and strip grade family (further details can be found in [26]). This model accounts for work-roll shifting but assumes constant pressure along strip width.

Backup roll wear model.

Similarly to the work-roll wear modelling, the backup roll wear is also formulated by a contact-mechanic equation. This equation assumes a simplified relation based on the cumulated rolling length of the backup roll and is written as,

$$W_{BUR} = k_{BUR} \cdot L_{BUR} [1 - bx^m] \quad (13)$$

where, W_{BUR} is the backup roll wear, L_{BUR} is the cumulated rolling length seen by the backup roll, k_{BUR} and b are backup wear tuning coefficients, m is an exponent coefficient and x is the relative position along the backup roll barrel width. The wear tuning coefficient k_{BUR} can be defined as function of the mill stand and the backup roll types.

PCFC Model Calibration

An automatic optimization methodology was deployed to calibrate the tuning coefficients of the PCFC sub-models. This methodology corresponds to an inverse optimization approach whose main goal is to seek for a set of model coefficients leading to the smallest difference between measurements

and model calculations [26,28]. To do this, the implemented calibration methodology combines an optimization algorithm, responsible for updating the unknown model coefficients, with a cost function, responsible for defining the gap between experimental and calculated data. During the optimization, the set of coefficients is iteratively updated with the purpose of minimizing the cost function value. Figure 3 summarizes the inverse optimization process framework developed to calibrate the tuning coefficients of the PCFC sub-models.

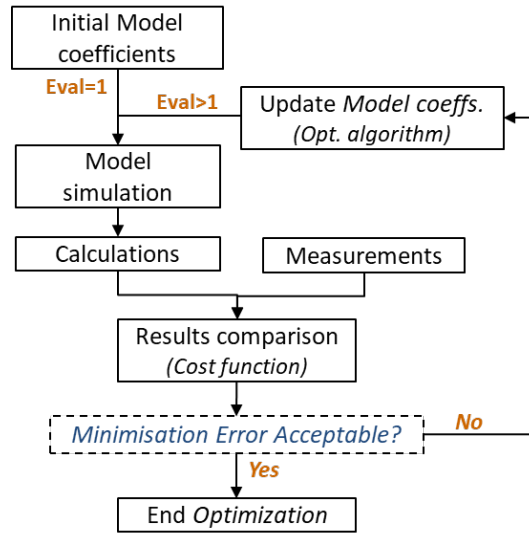


Fig. 3. Optimization framework used to calibrate PCFC wear and thermal crown sub-models [8].

In this automatic optimization methodology, the cost function plays a crucial role on the model calibration since the optimization process is guided by its minimization, so a suitable definition of this function is required. Here, the cost function (F_{cost}) used for calibrating the PCFC sub-models is defined by,

$$F_{cost} = \sum_{i=j}^{n_t} \frac{1}{n_p^n} \sum_{i=1}^{n_p^n} \left(\frac{\delta_{i,j}^{Ref} - \delta_{i,j}^{Calc}}{w_{abs,j}} \right)^2 \quad (14)$$

where n_t is the number of experiments (from different rolling campaigns or different stands), n_p^n is the number of points of each experiment, $\delta_{i,j}^{Ref}$ and $\delta_{i,j}^{Calc}$ correspond respectively to the reference and calculated values for each point i belonging to the experiment j and $w_{abs,j}$ is a weighting factor that must be normalized according to the different units or scales of the experiment j . A constrained optimization approach is applied by defining empirical upper and lower bound values for each one of the tuning coefficients subjected to calibration.

Roll wear model tuning.

In the case of the work-roll wear model, the optimization approach to tune the work-roll wear in the 7 hot finishing stands was split in 2 steps. Firstly, tune work-roll wear centreline amplitude (wear factor coefficient k) at all the stands using a reference database composed by work-roll wear profiles for 20 rolling campaigns. Secondly, once wear amplitude was calibrated, tune the work-roll wear shape across the full roll width (tuning coefficient a) considering the successive strip widths and roll shifting positions along the rolling campaigns. Figure 4 shows work-roll wear model calibration results obtained by applying the 2 steps tuning approach for the last 2 finishing stands (F6 and F7).

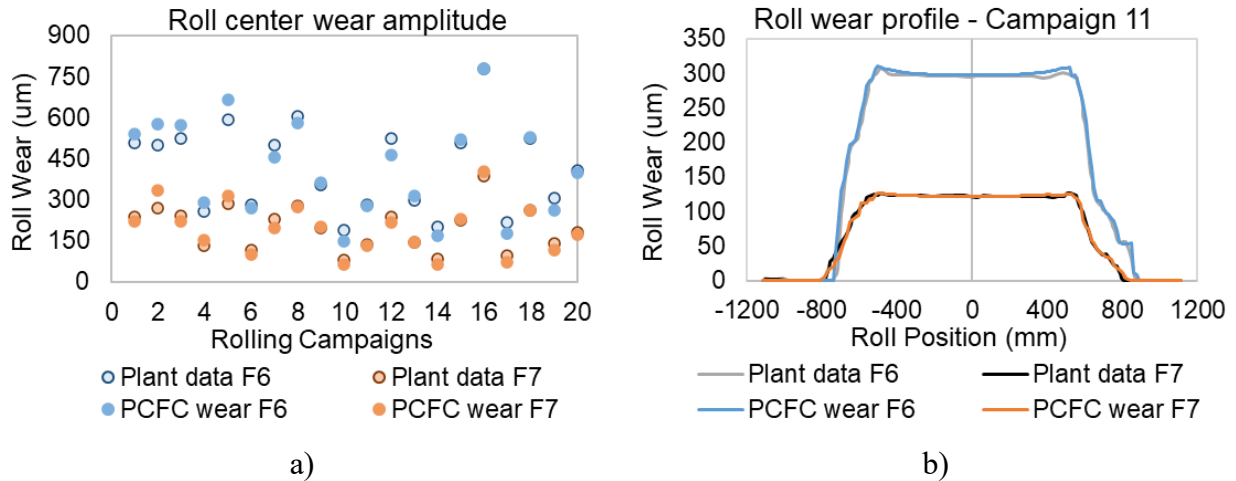


Fig. 4. Work-roll wear a) centreline amplitude for all campaigns and b) profile at end of campaign 11 predicted by tuned wear model (PCFC wear) and compared with reference data coming from the ArcelorMittal plant (called as Plant data).

Roll thermal model tuning.

For roll thermal model tuning, it is recommended to use both roll temperature and thermal crown profiles as reference data [28]. Nevertheless, only thermal crown profiles coming from the plant were available. Thus, the automatic tuning approach was applied to find the optimum parameters set only minimizing the gap between mill's thermal crown profiles and respective calculated profiles coming from the PCFC thermal model. Thermal crown profiles were calibrated for all the 7 finishing stands by using a reference rolling campaign and by tuning the heat transfer coefficients H_{strip} , H_{cool}^A and H_{cool}^B , respectively, for each one of the stands. Figure 5 shows the tuned PCFC thermal crown results obtained for all stands at the end of the rolling campaign.

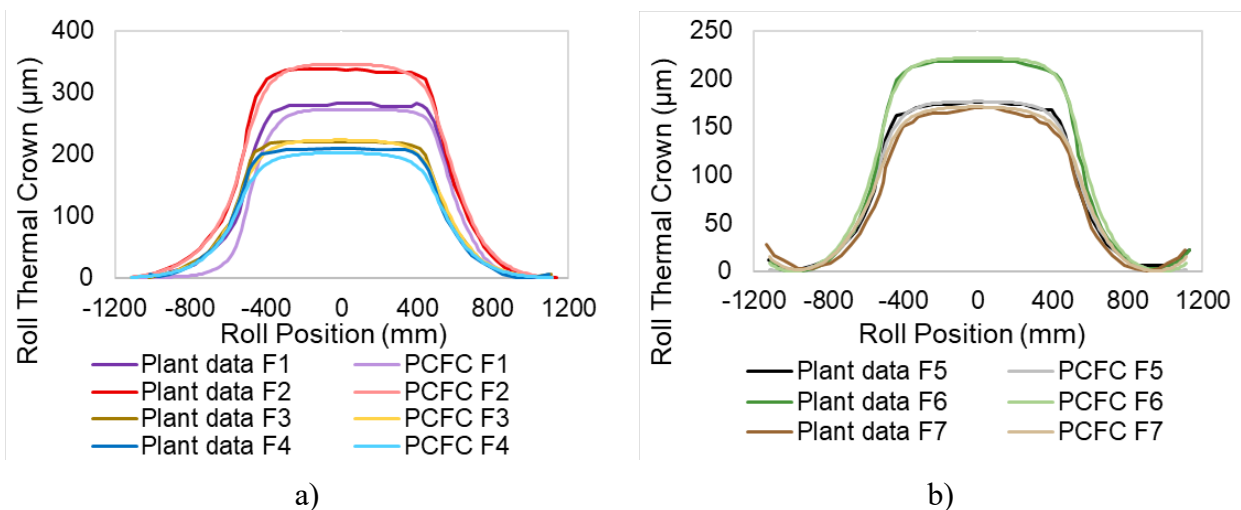


Fig. 5. Work-roll thermal crown profiles for stands a) F1-F4 and b) F5-F7 coming from tuned PCFC thermal model and reference data provided by the ArcelorMittal plant (called as Plant data).

Strip model tuning.

No calibration has been applied to fine tune the strip model coefficients. In this way, all the calculations were carried out with a standard set of parameters. These standard parameters are the same for all strip grade families. So, possible behaviour differences between strip families are not distinguished here on the strip model calculations.

PCFC Performance Analysis

The performance analysis of the developed PCFC model is carried out using industrial hot strip rolling data coming from an ArcelorMittal plant. This plant is equipped with seven 4-high stands (F1-F7) with individual roll bending and roll CVC-shifting actuators. A multi-function gauge system at the finishing mill exit measures strip crown profile and flatness for all the rolled strips.

After PCFC sub-models calibration, a comparison study between PCFC calculations, plant's supplier model predictions and real measurements was carried out by using a mill database composed by a dozen of schedules coming from different rolling campaign types (total of 1650 rolled strips). Both PCFC prototype and plant supplier's model calculations were carried out in recalculation mode and with no adaptation contribution to enable an unbiased performance assessment between both PCFC solutions.

PCFC prototype calculations were compared with exit finishing mill measures (exit stand F7) for all strip crown indicators C25, C40 and C100 and for the strip flatness indicator Flat100. However, only C40 and Flat100 predictions from PCFC prototype and PCFC plant's supplier model could be compared since strip indicators C25 and C100 outputs were not available in the supplier solution running at the mill.

Figure 6 summarizes the comparative performance between PCFC prototype and plant's PCFC supplier model with respect to strip crown C40 and flatness Flat100 for the different rolling campaign types investigated. Encouraging results were obtained from this performance assessment since PCFC prototype tends to lead to similar behavior compared to the plant's PCFC supplier model:

- Strip crown C40 gap ($\Delta C40$) between measures and models was in average $\approx 10 \mu\text{m}$ for PCFC supplier model and $\approx 16 \mu\text{m}$ for the developed PCFC prototype. So, PCFC prototype C40 strip crown predictions tend to be, in average, a bit less accurate than the ones coming from the supplier PCFC solution ($\approx 6 \mu\text{m}$ gap) when compared to the exit mill measures.
- Strip crown C40 predictions obtained by the PCFC prototype model were similar to the ones from the plants PCFC supplier model for harder rolling campaigns (D, E, H) but less accurate for softer rolling campaigns (B, C, G). In the case of high carbon (A) and thin material (F) rolling campaigns, C40 strip crown predictions from PCFC prototype were below $\approx 10 \mu\text{m}$ (total gap average between measures and PCFC supplier model predictions).
- Strip flatness Flat100 gap ($\Delta \text{Flat100}$) between measures and models was in average ≈ 45 I-Units for PCFC supplier model and ≈ 13 I-Units for the developed PCFC prototype. So, strip flatness was better predicted by the PCFC prototype since the calculations were in average ≈ 32 I-Units more accurate than the ones from the PCFC supplier's solution.

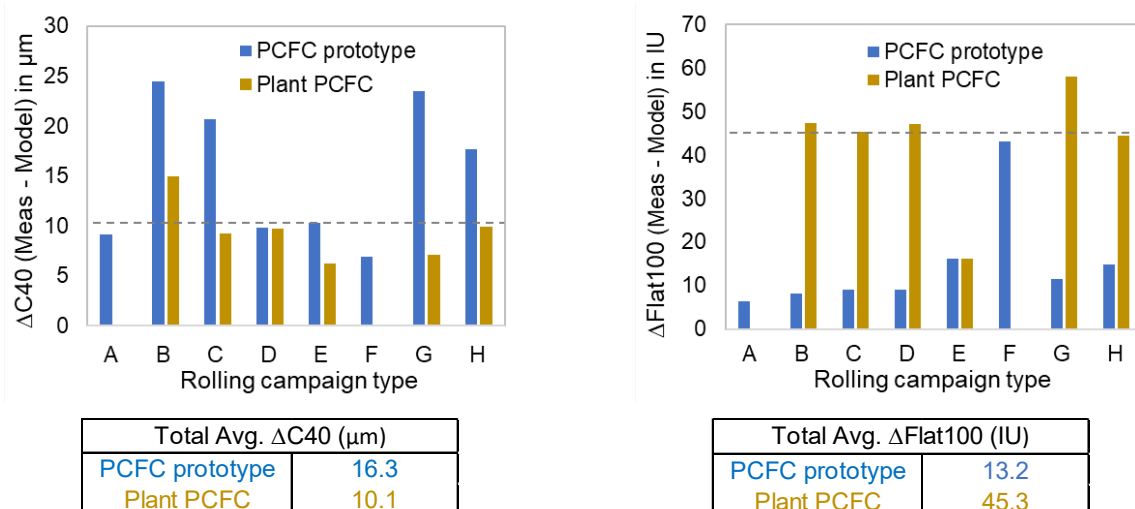


Fig. 6. Statistics for strip crown C40 and flatness Flat100 results obtained by the PCFC prototype model developed and plant supplier's PCFC model (called as Plant PCFC) for the different rolling campaign types evaluated. No supplier PCFC predictions could be extracted for campaign types A and F but mill measures were available.

Additional observations were also obtained from the detailed analysis of the measured and calculated strip crown and flatness indicators (C25, C40, C100 and Flat100) all along the rolling campaigns investigated. Figure 7 shows the measured and calculated strip crown and flatness indicators over one of the rolling campaigns of type D (composed by hard grades). From these results, it can be stressed out that:

- PCFC prototype calculations tend to follow the same trend than strip crown measures over most of the rolling campaign revealing that this PCFC prototype seems able to well capture the coil-to-coil strip crown variations.
- PCFC prototype strip flatness (Flat100) predictions were significantly better than the ones coming from plant's PCFC model. Actually, plants' PCFC supplier model seems not able to give satisfying flatness predictions at the finishing mill exit and so, a correction by coil-to-coil regulation is usually applied for last stand.

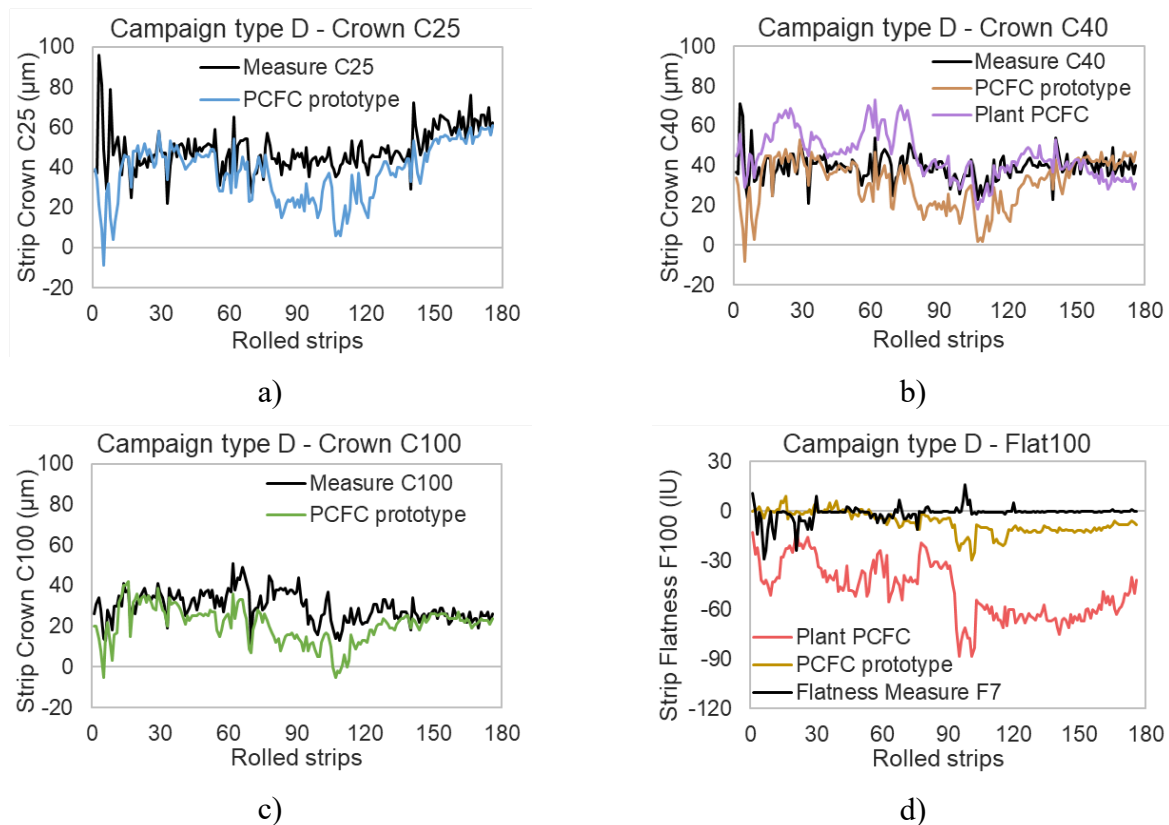


Fig. 7. Strip crown a) C25, b) C40, c) C100 and flatness d) Flat100 indicators measured at the mill stand F7 exit and calculated by both PCFC models for a rolling campaign type D. Suppliers' PCFC model results (Plant PCFC) only available for C40 and Flat100 indicators.

To complement the performance analysis, full strip profiles obtained by the developed PCFC model prototype and plants' PCFC supplier model for some strips of one of the rolling campaigns have also been compared with the ones coming from the measures at the exit of the finishing mill. These calculated strip profiles, shown in Figure 8, reveal that the PCFC prototype model seems able to deliver satisfying prediction of the full strip profile shape when reliable calculation of strip crown C40 is reached (case of strip 30). However, strip profile predictions from plant's PCFC solution still tend to outperform the ones from the PCFC prototype because this last one is not yet distinguishing behaviour differences between strip families on the strip model calculations.

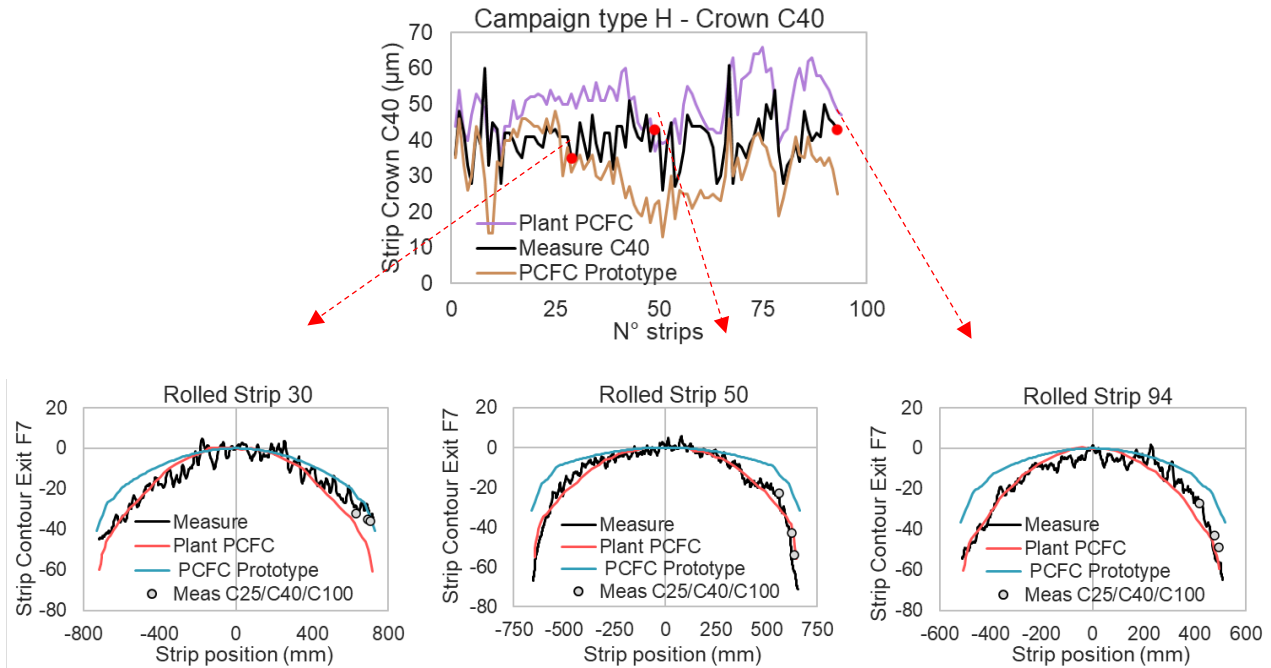


Fig. 8. Strip crown profiles measured and calculated by both PCFC models at the exit of F7 stand for different strips of a rolling campaign type H.

Conclusion

A full PCFC model including several physical based sub-models calculating the different contributions to the roll gap was developed with the purpose of predicting strip crown and flatness profile for hot finishing mills. In addition, an inverse parameters identification approach was also developed and applied to effectively tune the unknown parameters of the sub-models of this PCFC prototype.

A performance analysis of the PCFC model prototype was then carried out by comparing its predictions against plant's PCFC supplier model calculations and mill measures for an industrial mill database composed of a dozen of schedules coming from different rolling campaign types. Strip crown and flatness indicators (C25, C40, C100 and Flat100) as well as full strip profiles results were compared by running both PCFC prototype and plant's models in recalculation mode and without adaptation contribution to allow a fair comparison between the calculated results.

The overall performance study carried out led to encouraging results since the developed PCFC model prototype tends to give strip crown and flatness predictions similar to the ones obtained by the plant's PCFC model (coming from an industrial supplier).

Moreover, all the PCFC prototype calculations were carried out using the same set of strip model parameters for the different rolling campaign types analyzed. So, PCFC prototype predictions can still be improved in the future by tuning specific strip model parameters sets for different strip families defined by the plant (distinguishing strip model behavior for harder and softer grades). The PCFC prototype performance assessment carried out here led to very promising results and confirms that this developed PCFC solution shows high potential for an online industrial implementation on Hot Finishing Mills.

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References

- [1] Sato M, Kuchi M. Profile and Flatness Set Up System for Rolling Mill. *IHI Engineering Review* 2009;42:26–31.
- [2] K.N. Shohet, N.A. Townsend. Roll Bending Methods of Crown Control in Four-high Plate Mills. *Journal of Iron and Steel Institute* 1968:1088–98.
- [3] Bald W, Beisemann G, Feldmann H, Schultes T. Continuously variable crown (CVC) rolling. *Iron and Steel Engineer* 1987;64:32–41.
- [4] Wang X, Li F, Li B, Dong L, Zhang B. Design and Application of an Optimum Backup Roll Contour Configured with CVC Work Roll in Hot Strip Mill. *ISIJ International* 2012;52:1637–43. <https://doi.org/10.2355/isijinternational.52.1637>.
- [5] Seilinger, A., Mayrhofer, A., Kainz, A. SmartCrown - a new system for improved profile and flatness control in rolling mills. *Rev Met Paris* 2003;100:43–8. <https://doi.org/10.1051/metal/2003001>.
- [6] Guo R-M. Characteristics of Rolling Mills with Roll Shifting. *Iron and Steel Technology* 1988;65:45–54.
- [7] Zhao J, Wang X, Yang Q, Wang Q, Liu C, Song G. High precision shape model and presetting strategy for strip hot rolling. *Journal of Materials Processing Technology* 2019;265:99–111. <https://doi.org/10.1016/j.jmatprotec.2018.10.005>.
- [8] Li H, Xu J, Wang G, Shi L, Xiao Y. Development of strip flatness and crown control model for hot strip mills. *Journal of Iron and Steel Research International* 2010;17:21–7. [https://doi.org/10.1016/S1006-706X\(10\)60067-2](https://doi.org/10.1016/S1006-706X(10)60067-2).
- [9] D. Ehlert, O. Jepsen, G. Schneider. OPTIMIZATION OF HIGH QUALITY PRODUCTION IN HOT ROLLING MILLS USING ADVANCED PROCESS MODELS. 52nd Rolling Seminar, Rio de Janeiro 2015:99–108. <https://doi.org/10.5151/1983-4764-26275>.
- [10] Peng K, Zhong H, Zhao L, Xue K, Ji Y. Strip shape modeling and its setup strategy in hot strip mill process. *The International Journal of Advanced Manufacturing Technology* 2014;72:589–605. <https://doi.org/10.1007/s00170-014-5649-2>.
- [11] Auzinger D, Gjumlija G, Nijhuis T, Seilinger A, Widder M, Posch G, et al. Application of advanced technology packages for improved strip profile and flatness in hot-strip-mills. *Rev Met Paris* 2003;100:977–86. <https://doi.org/10.1051/metal:2003111>.
- [12] Deng J, Sierla S, Sun J, Vyatkin V. Physics-informed generative regression for industrial process modeling in steel strip rolling. *Expert Systems with Applications* 2025;282:127713. <https://doi.org/10.1016/j.eswa.2025.127713>.
- [13] Wang Z, Huang Y, Liu Y, Wang T. Prediction Model of Strip Crown in Hot Rolling Process Based on Machine Learning and Industrial Data. *Metals* 2023;13:900. <https://doi.org/10.3390/met13050900>.
- [14] Liu Y, Wang X, Sun J, Liu G, Li H, Ji Y. Strip Thickness and Profile–Flatness Prediction in Tandem Hot Rolling Process Using Mechanism Model-Guided Machine Learning. *Steel Research International* 2023;94:2200447. <https://doi.org/10.1002/srin.202200447>.
- [15] Song C, Cao J, Sun L, Tan X, Xia W, Sun S. A multi-stand work roll bending and shifting approach for profile contour and flatness control of electrical steel in multi-width schedule-free rolling using NSGA-II algorithm. *Journal of Manufacturing Processes* 2024;120:895–910. <https://doi.org/10.1016/j.jmapro.2024.05.016>.

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- [16] Deng J, Sun J, Peng W, Hu Y, Zhang D. Application of neural networks for predicting hot-rolled strip crown. *Applied Soft Computing* 2019;78:119–31. <https://doi.org/10.1016/j.asoc.2019.02.030>.
- [17] Meng LM, Ding JG, Dong ZS, Li X, Zhang DH. Crown Prediction of Hot-Rolled Silicon Steel Using Transfer Learning Network Fused with Whale Optimization Algorithm. *Steel Research International* 2023;94:2300105. <https://doi.org/10.1002/srin.202300105>.
- [18] Ji Y, Wen Y, Peng W, Sun J. Predicting Hot-rolled Strip Crown Using a Hybrid Machine Learning Model. *ISIJ International* 2024;64:566–75. <https://doi.org/10.2355/isijinternational.ISIJINT-2023-203>.
- [19] Song L, Xu D, Wang X, Yang Q, Ji Y. Application of machine learning to predict and diagnose for hot-rolled strip crown. *The International Journal of Advanced Manufacturing Technology* 2022;120:881–90. <https://doi.org/10.1007/s00170-022-08825-w>.
- [20] Song C, Cao J, Xiao J, Zhao Q, Sun S, Li Y. Control strategy of multi-stand work roll bending and shifting on the crown for UVC hot rolling mill based on MOGPR approach. *Journal of Manufacturing Processes* 2023;85:832–43. <https://doi.org/10.1016/j.jmapro.2022.11.075>.
- [21] Shang F, Chen H, Wang S, Zhao J, Ma Y, Ba Y. Machine learning-based process parameter optimisation and strip plate shape improvement in steel production. *Ironmaking & Steelmaking* 2025;52:975–1010. <https://doi.org/10.1177/03019233251359803>.
- [22] Hacquin A, Montmitonnet P, Guillerault JP. A three-dimensional semi-analytical model of rolling stand deformation with finite element validation. *European Journal of Mechanics - A/Solids* 1998;17:79–106. [https://doi.org/10.1016/S0997-7538\(98\)80065-X](https://doi.org/10.1016/S0997-7538(98)80065-X).
- [23] A. Hacquin. Modélisation thermomécanique tridimensionnelle du laminage: Couplage bande-cylindres (in french). PhD. Thesis. Ecole des Mines de Paris, 1996.
- [24] K. Nakajima, T. Asamura, T. Kikuma, H. Matsumoto. Hot strip crown control by 6-high mills. *Iron and Steel Institute of Japan* 1984;24.
- [25] S. Timoshenko, J. N. Goodier. *Theory of Elasticity* (pp. 406-410). McGraw-Hill book; 1951.
- [26] N. Souto, E. Marchand, A. Gay, Z. Koont, N. Legrand. Performance Analysis of Work-Roll Wear Models on Hot Rolling. *Key Engineering Materials* 2022;926:621–31.
- [27] Archard JF, Hirst W. The Wear of Metals under Unlubricated Conditions. *Proceedings of the Royal Society of London Series A, Mathematical and Physical Sciences* 1956;236:397–410.
- [28] N. Legrand, N. Souto, S. Abdelkhalek, Z. Koont. Tec3 Work-Roll Thermal Crown Model for Hot and Cold Rolling of steel. *11th International Rolling Conference (IRC 2019)* 2019:955–66. <https://doi.org/10.5151/9785-9785-32510>.