Advanced Profile Control: Model – Optimization – Contour

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For profile and flatness control, on-line process models provide a detailed and validated description of roll stack deflection and material flow, i.e., pressure distribution in the roll gap. With a collection of process data included in the model-based profile setup, the on-line calculations can be completely reproduced off-line. Combining this feature with standard mathematical optimization allows for model parameter optimization. Here internal model parameters can be optimized along with externally supplied data such as roll properties. This minimizes the deviation between calculated and measured strip contour. Besides faster commissioning, optimized models allow for simple profile control to highly sophisticated contour control.

Profile and Contour Model

Even when people on the mill operation side or equipment suppliers talk about the "profile model," there is no such single model to describe the strip contour in the roll gap. Such a model is always an interaction of many models, which describe different physical aspects acting in the rolling process and giving the strips some contour. In the case presented here, such models are:

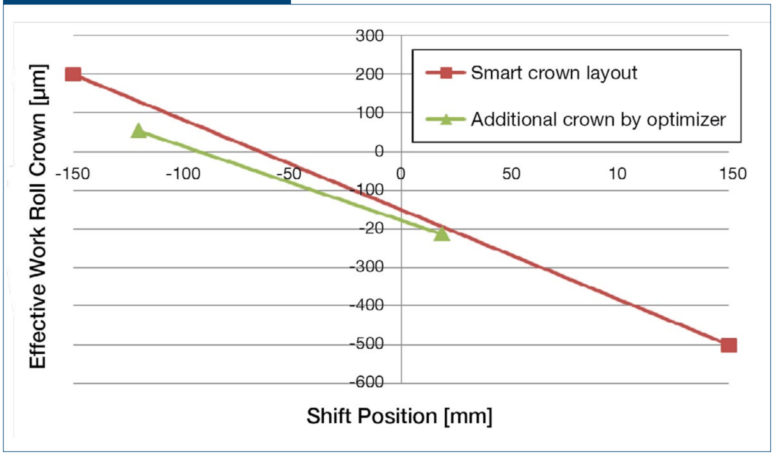
- Work roll flattening model, which describes elastic deformation of the work roll at the interface to the strip.
- Roll deflection model, which is capable of calculating the bending lines of the rolls in a 2-, 4- or 6-high roll stand, including the roll flattening at the roll-roll interfaces dependent on current roll crown conditions.
- Roll temperature and wear model, which is an on-line monitor of the current status of all rolls in all roll stands regarding temperature, the resulting temperature crown and of wear crown.
- Material flow model, which derives the pressure distribution in the roll gap from the entry and exit contour of the strip at the roll bite.
- A setup strategy for how to reach a target strip profile in several passes using different actuators such as work roll bending, work roll shifting or pair cross.

Details about the elastic deformation of work rolls and the roll-roll-interface can be found in Reference 1. In Reference 2, details for material flow modeling are described.

Those models are connected in the profile model, i.e., their interfaces must be supplied with the necessary data and iterations must be performed to generate self-consistent solutions since the output of some models is the input of others and vice versa. In the case of a contour model, the necessary data comprises:

- Young's modulus of work and backup rolls — the shell material distinguished from the core material.
- Roll forces, entry and exit strip thickness for every pass, and strip width.
- Roll cooling flows, cooling characteristics of nozzles, circumferential turning speed

Figure 1



Effective work roll crown as a function of the work roll shifting position.

of the rolls, and heat transfer from the strip into the roll as well as from the roll into the cooling water.

- Frictional conditions in the roll bite.
- Precise description of the roll geometry regarding grinding, e.g., Smart Crown technology, work roll tapers and backup roll chamfers.

For sure, this list is not complete, but it can be seen that there are many parameters to be supplied. The advantage of using physical process models is their flexibility. If, for example, a mill operating team changes the work rolls toward HSS rolls, just the physical parameters have to be provided. Or if new grinding curves are used because the spectrum of rolled products shall be increased, only the new parameters have to be provided to the model to continue production. This keeps the producer flexible.

On the other hand, as the setup must be seen as a model predictive controller, the quality of the setup depends very much on the quality of the data supplied to the model. In this case, is the Young's modulus of the installed work rolls really 180 GPa or is it 195 GPa? Is the wear parameter of the new rolls the same as for the old ones? In the past, model results quite often suffered from incomplete and imprecise data supplied to the models. Therefore, a simple but very efficient strategy has been developed to help with this issue.

Model Optimization

Principle — During production, the L2 process wrapping the profile model writes all model inputs into files, which allows for an off-line repetition of this calculation on another computer at any time as often as required. Now it is straightforward to connect this off-line model calculation to a standard optimizer such as sequential quadratic programming (SQP).[3,4] The cost function to be minimized is the deviation of the model calculated result from the measured result. In the case of contour this means:

$$\text{cost}(p_1,\ldots,p_n) =$$
$$\sum_{\#\text{strips}}\sum_{\#\text{scans}}\sum_{x\in\text{traces}}\left(\text{contour}_{\text{meas}}(x)-\text{contour}_{\text{calc}}(x)\right)^2+\mu\sum_{i=1}^{n}\left(p_i-p_i^0\right)^2 \quad \text{(Eq. 1)}$$

where

p_i = the parameters under consideration,
p_i^0 = the initial value for the optimization and
μ = a small parameter for regularization.

Example 1: Identification of a Mismatch in Work Roll Grinding — In a recent plate mill project, problems regarding the shifting setup accuracy arose after installation of new Smart Crown grinding. The idea was to let the optimizer correct the effective work roll crown as a linear function of the actual shifting position. So two optimization parameters have been introduced: crown correction for minimum and crown correction for maximum applied shifting position. For the optimization, 206 rolling schedules of different plates rolled in this mill were used. Only the values of a 3-point gauge have been available as measurement. Using the optimizing strategy described above, the root mean square error between the model calculation and the measurement has been significantly reduced from the initial value of 104 µm to 35 µm.

As can be seen in Fig. 1, the optimizer added almost the same crown correction to the work rolls as the original Smart Crown layout shows. A few investigations later, it was obvious that the grinding shop applied the grinding curves radius-based, while they were specified diameter-based. This immediately explained the higher efficiency of the work roll shift on the profile. Doubling the coefficient for the SmartCrown grinding amplitude in the model input immediately improved the situation of profile control performance toward contractual FAC conditions.

Example 2: Identification of Backup Roll Chamfer Extent — In the course of a hot strip mill project, the model indicated dogbone–type contour anomalies especially on wide strips, which could not be seen in the profile gauge readings to the same extent. According to the authors' experience, the typical source for such an anomaly is either thermal crown or backup roll chamfer. The optimizer was started on a very small set of four wide strips with a total of 300 contour scans and was allowed to change both the amplitude of the thermal crown — the same factor for all work rolls in the finishing mill — and the extent of the backup roll chamfer at the same time. The optimizer hasn't done much on the thermal crown, but has reduced the backup chamfer by 65 mm on each side. The root mean square deviation between calculation and measurement of the strip contours was reduced from 10.5 µm to 6.6 µm. Fig. 2 compares the model calculated contour before (native) and after optimization for one strip with the corresponding measured contour.

Based on these model optimization results, study of the chamfer was continued and manual measurements were performed with a straddle gauge on the recently ground backup rolls. Fig. 3 shows the results.

It can be seen in Fig. 3 that indeed the chamfer hasn't been as sharp as it has been supplied to the model. A quadratic chamfer was supplied to the model, which doesn't show the kink and is closer to the manually measured one. This improved the setup quality significantly and at once. Meanwhile, the ground backup roll chamfer geometry was revised for other reasons.

Tiny Summary — Model optimization can:

- Give a clue to rough supply errors during commissioning of the profile model.
- Improve the model quality for better results and thus lower adaptation.

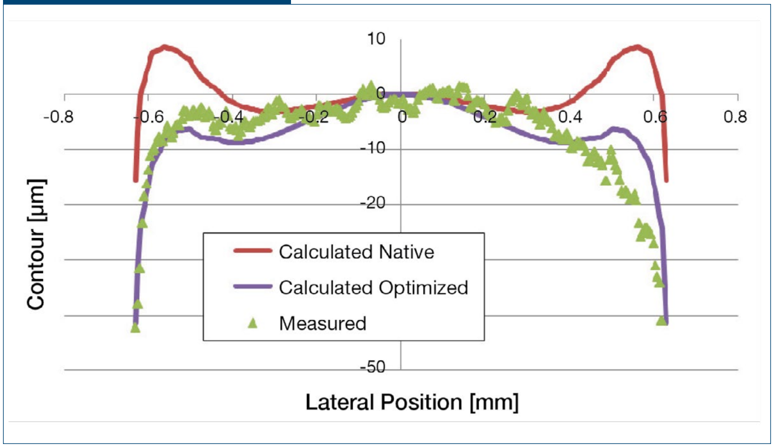
With an optimized profile model, the next step is contour control.

Contour Control

Contour vs. Profile — Before diving deep into contour control, it is important to understand the fundamental difference between profile and strip contour. Profile is, as is widely known, a single value describing the difference between thickness at the strip center and thickness at the edges. In fact, edge thickness is measured some xx millimeters away from the edges and averaged over the two sides. The respective profile value is called Cxx, e.g., C40 if edge thickness is measured 40 mm from the edges. Contour is the thickness distribution across the strip width. Consequently, profile is the evaluation of contour only at three points with information condensed to a single value. Furthermore, higher-order information such as gradient and curvature is lost.

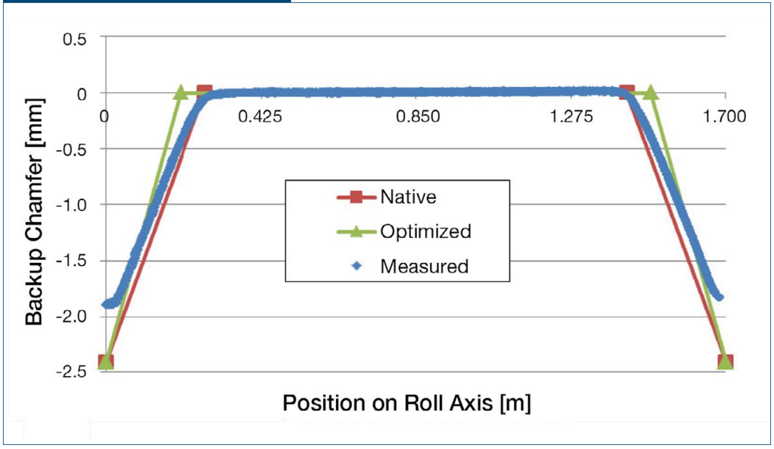
In recent years, contour has played an increasing role for strip producers for two major reasons: first, the end customers' demand for pre-defined strip contours to improve their further production. Consider, as an example, a hot strip mill. Their typical end customers are cold mills and the direct processing industry. Whereas the cold mill requests for more "round" contours that can be described by a profile value more or less sufficiently, the direct processing industry typically requests almost rectangular cross-sections

Figure 2



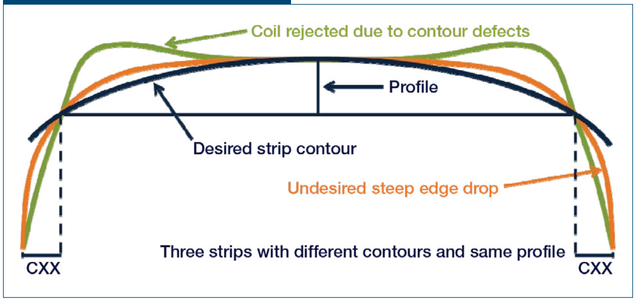
Comparison of model calculated (native and optimized) with measured contour.

Figure 3



Backup roll chamfer as specified (native), optimized to make the model match the measured strip contour and manually measured with the straddle gauge.

Figure 4



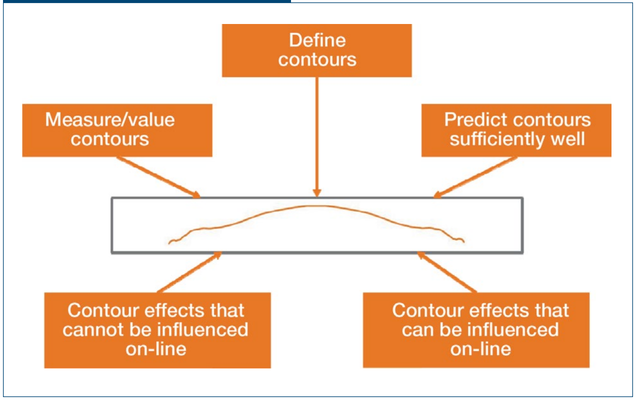
Three strips showing the same profile but different contours.

where additional information is necessary. Second, in today's complex rolling scenarios with a large variety of different rolled materials and small lot sizes, undesired contour errors may occur. To describe, detect and act against these defects, contour and not just profile has to be taken into account. Fig. 4 shows three strips having the same profile value but significantly different strip contours.

There is an important difference between the two reasons for considering contour instead of profile mentioned above. On the one hand, there is a desire to modify the strip contour to meet a pre-defined contour, and, on the other hand, there is a need to avoid occurring contour defects. To be able to control contour, different aspects have to be considered (Fig. 5).

The first aspect is to clarify the definition of contours, i.e., which shapes can be considered as favorable contours, and, in addition, indicators that are relevant for contour defects (Fig. 6). In addition to profile and edge drop, a definition for the well-known thickening at the strip edge is proposed, as terminology is not standardized: within a certain region at the strip edges on operator and drive side, respectively, the maximal thickness of the strip is determined, i.e., the contour maximum. If one of these two maxima is greater than the thickness at strip center, the strip is rated as dogbone. Starting from these maxima, the minimal thickness is determined within another region closer to the strip center. If one of these minima has a sufficiently smaller thickness than the corresponding maximum, the strip is rated as thick edge. Note that profile, edge drop and dogbone may result in arbitrary values; the thick edge value is always non-negative and is zero if there is no thick edge, no matter how curvy the contour is in the evaluated ranges. For dogbones, this measure also provides information on how close a strip is to having them. As not all of these relevant contour indicators might be satisfied perfectly at the same time, it is reasonable to rate them and to provide ranges where they are considered to be good. For example, a slightly higher profile within given tolerances might prevent a strip from getting dogbones. Rating contour defects also reflects that some of them are more severe in some cases than others, e.g., dogbones have to be suppressed in almost all cases.

Figure 5



Different aspects for contour control.

Figure 6

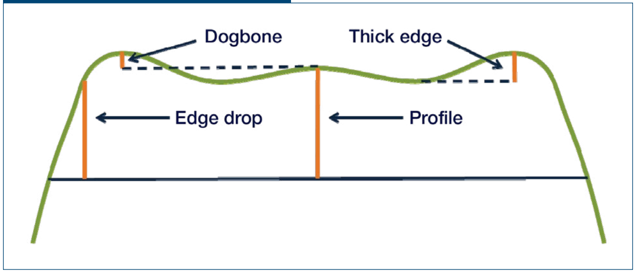


Illustration of contour-relevant indicators and defects.

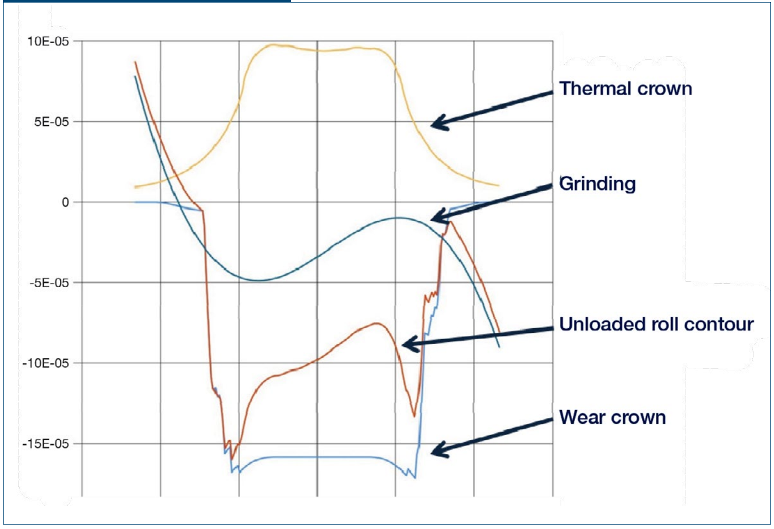
Contour Defects — Defining contour defects as dogbone and thick edge in some regions is beneficial instead of just measuring the strip contour at other positions Cyy in addition to the Cxx value for the strip profile. For example, the location of the maxima and minima may vary with respect to the strip edge over short-term inherited strips. Hence, a pure position-based determination detects improvements or deteriorations in the strip contour although they just shifted a bit.

Moreover, asymmetric contour errors can be described as well, employing the definition of thick edges and dogbones when determined for each side separately. In addition, further asymmetric values can be determined, such as wedge.

The second aspect is to have a reliable prediction or recalculation of contours. To obtain this, the optimized profile model described above is utilized using, e.g., numerical methods like SQP. The use of as much contour information as possible and to avoid compression to, e.g., quadratic polynomials, in particular in the transition between pre- and post-calculation within the profile model is crucial.

The third aspect is the contour measurement of the rolled strip. Here, contour gauges that provide reliable data up to the strip edge are important. Having calculated and measured contours, their shapes and deviations can be evaluated quantitatively. A simple measure to value contours can be of root mean square type, similar to Eq. 1, where the difference between calculated and measured contours is determined pointwise. But also other measures like for monotonicity or curvature can be applied, or a combination of them.

Figure 7



Work roll sum-crown (unloaded roll contour) and contributions to it.

Contour Control — The first three aspects provide definitions and calculation strategies to deal with contours. The following aspects are about the question of what affects contour. Here, the distinction between contour effects that can or cannot be modified on-line, i.e., within some profile, flatness and contour control, is made. The roll grinding is a typical example that cannot be modified on-line. On the other hand, the adjustment of actuators such as bending, shifting or pair cross, if available, can be done on-line and can thus be used within a profile, flatness and contour control.

The main components that affect strip contour are:

- Shape of the unloaded roll contours.
- Thickness and profile distribution over the mill stands and the resulting bending and flattening of rolls induced by the deformation of the roll stack when loaded and actuators adjusted.
- Material properties and dimensions of the roll stack and the rolled material.
- Roll tilting and lateral displacement of the strip.

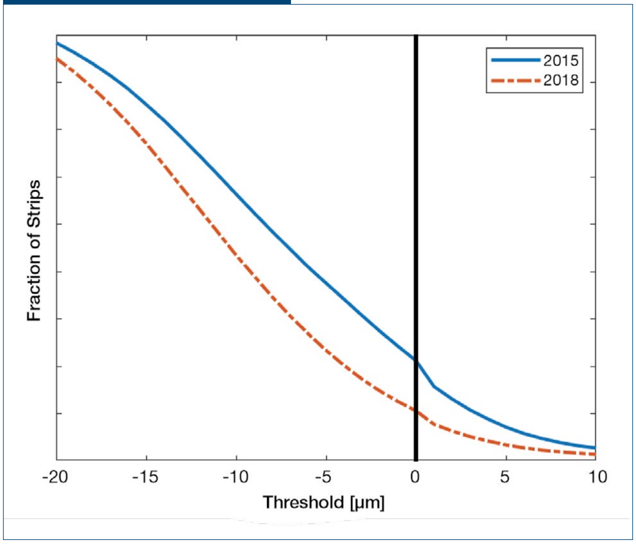
The shape of the unloaded roll contour, mainly the work roll contour, textures the strip, i.e., defects on the roll contour are directly rolled onto the strip. The unloaded roll contour consists mainly of three components: thermal crown, wear crown and roll grinding, including even backup roll chamfers. Although each of these components may look fine, the resulting roll contour may not (Fig. 7). In this example, severe so-called "vampire teeth"-like marks occur in the shape of the roll exactly where dogbones on the strip occur. To avoid this, all three components need to be adjusted, for example by specialized grindings, shifting strategies to modify the shape of wear and thermal crown, or modified cooling and/or heating of rolls and/or the strip, depending on the equipment of the mill. Again the mathematical optimization strategies described here can be used for improved adjustment of the mill. These strategies can be seen as on-line and off-line actuators that mainly help to reduce contour defects. But, in particular, the control of the thermal crown is also an actuator to meet pre-defined target contours as it is able to modify contour locally.

Furthermore, thickness and profile distribution play an important role for contour. They affect the load distribution over the mill stands and thus influence the bending and the flattening of the rolls, which, in turn, is part of the resulting roll contour. This provides additional actuators to improve contour and to reduce contour defects. Moreover, the material to be rolled and the general layout of the plant are important for contour, but are typically given and cannot be modified easily. What is done to modify contour in this point is the usage of different roll types, in particular HSS rolls.

All the above-mentioned effects — some of them can be modified actively, some not — influence the resulting contour indirectly. Hence it is difficult to meet a customer-defined target contour by using them. But again, by having sufficiently precise process models at hand that calculate these effects, the target contour of a strip can be specified rather than only a profile value. Even long-term and short-term adaptations can be employed to improve quantitative results. See Eq. 1, where the target contour, which is typically a parabola representing the profile value, can easily be replaced by an arbitrary but obviously reasonable function.

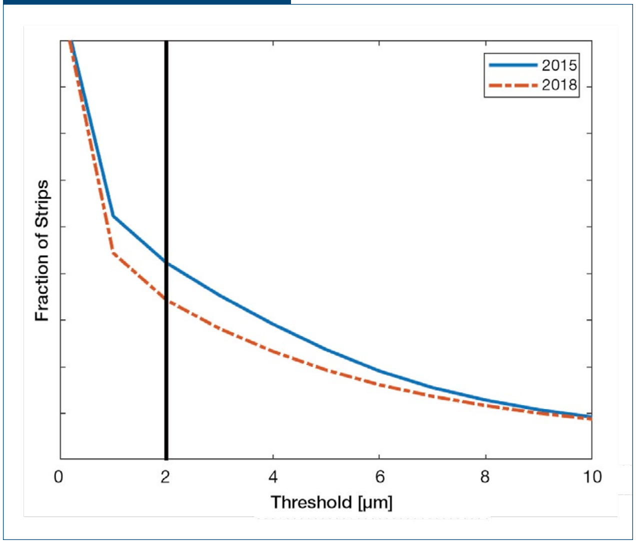
Mainly for asymmetric contour defects, tilting and lateral displacement play an important role. If the wedge of a strip and the tilting of the rolls do not match, cambers occur that, in turn, result in lateral

Figure 8



Fraction of strips with measured dogbone at operator side in years 2015 (solid line) and 2018 (dashed line).

Figure 9



Fraction of strips with measured thick edge at operator side, again in years 2015 (solid line) and 2018 (dashed line).

displacements of the strip in the subsequent stands. Sometimes a wedge is already introduced to the strip in the roughing mill. If a strip enters a mill stand with lateral displacement, i.e., offset from the stand center, the roll stack deflection is not symmetric anymore and contour defects appear. Moreover, hitting the steep edges of thermal and wear crown results in severe local defects at the strip edge. Thus a high-performance strip steering is beneficial.

The distinction of thick edges and dogbones helps to understand the occurrence of the described contour defects as their origins often can be assigned to different effects. As seen in Fig. 2, the length of the backup roll chamfer mainly results in dogbones, as well as bad shape or misalignment of thermal and wear crown. On the other hand, the profile distribution over stands affects thick edges.

Results — Within a cooperation on strip contour between thyssenkrupp Hohenlimburg GmbH and Primetals Technologies Germany GmbH, some of the aspects denoted earlier were modified and optimized to improve strip contour. Up to now, this reduced the number of strips rated with thick edge by 15.5% and those with dogbone by 48.8% (Figs. 8 and 9). In both figures, the fraction of strips with measured dogbone or thick edge, respectively, at operator side lower or equal to a given threshold is shown. The vertical lines show the given thresholds by thyssenkrupp Hohenlimburg, i.e., for dogbones there is the threshold at 0 µm and for thick edges at 2 µm. This means that the edge of the strip must not be thicker than the strip center and only very small thick edges are tolerable. Further improvements are currently ongoing aiming at non-parabolic target contour definitions.

Conclusions

This paper discussed the models required to calculate strip contours in a hot rolling mill. It has been shown how to optimize model input and model parameters using real process data to decrease the dependency on on-line adaptation. This kind of optimized profile model is considered contour ready, because the modeled strip contours show many features of the measurements. Besides the profile Cxx value, other characteristic numbers such as for dogbone and thick edge have been derived to describe contour anomalies. The paper also showed how the appearance of contour anomalies at the thyssenkrupp Hohenlimburg rolling mill were reduced by consequent improvements of the process model.

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