Improved strip profile and flatness control in hot strip mills

By combining improved modelling of roll wear and thermal expansion with an on-line 3D roll stack deformation model, a new strategy to establish a certain roll gap shape for each stand by use of roll gap actuators can be employed which significantly improves strip profile and flatness.

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Good profile and flatness control for hot-rolled strip is based on:

- Precise knowledge of the shape of the unloaded rolls
- Exact description of the deformation of the roll stack under rolling conditions
- An effective profile and flatness setup and control strategy, making the most efficient use of the existing profile actuators

Based on VAI’s on-line 3-D roll stack deformation model, which combines the accuracy of a detailed finite element model with the advantage of very short calculation times, voestalpine Stahl and VAI are working in partnership to significantly improve profile and flatness control. Initially the dynamic effects affecting the shape of the unloaded rolls, namely roll wear and thermal expansion, were investigated, and excellent accuracy was achieved. Currently a completely new setup and control strategy for optimised profile and flatness performance is under development.

INTRODUCTION

voestalpine Stahl completely revamped its automation system in 1995, which included a setup and control system for strip finishing mills, however, in order to satisfy increased quality requirements on hot band, it signed a cooperation agreement with VAI in 2000 to further improve profile and flatness setup and control.

The core modules of VAI’s Advanced Profile and Flatness Control System are:

- 3-D on-line roll stack deflection model
- Thermal crown model
- Roll wear model
- Flexible profile and flatness setup strategy
- Closed loop flatness control
- Problem-specific model adaptation based on profile and flatness measurement

ADVANCED PROFILE AND FLATNESS CONTROL SYSTEM

3D on-line roll stack deflection model

VAI had already developed an ultra-fast 3D on-line finite element program to calculate the deformation of the roll stack. In the on-line roll stack deflection models that have been used up to now, the rolls of the roll stack are modelled in a simplified way and the deformation is calculated by a variety of methods based on simple solutions of elasticity theory (beam under transverse load, bar bent by couples, deformation of a half space by locally applied forces, etc). This approach has only limited accuracy because of neglected effects and the approximations used. To improve accuracy, VAI decided to use mathematical modelling for the on-line calculation without simplifications. Figure 1 illustrates a model output showing the contact area and contact pressure between work roll and backup roll, and contact area between work roll and rolled material.

VAI’s on-line roll stack deformation model means:

- A fully 3D elasticity theoretical modelling of the roll, taking into account the actual geometry of roll barrel and roll necks
- Roll bending and flattening are modelled without simplifications
- Dimensions and material properties of roll core and shell are precisely considered
- The real 2D pressure distribution between two rolls in contact and the corresponding contact area are iteratively calculated based on the actual contour of...
models, the new roll stack deflection model was initially installed on an off-line computer. To achieve a flat strip at the exit of the last finishing stand, the roll gap shape and the strip profile should be matching, and so the predicted roll gap shape was compared with the measured strip profile. A two-month trial very clearly showed that there was still much work to do.

The comparison of measured and calculated roll gap profile is strongly affected by the accuracy of the profile gauge (not better than $\pm 10 \mu m$ for the existing gauge and a new one is just being commissioned). Although the roll gap profile and the strip profile only completely agree in the case of a perfectly flat strip, and visual unflatness (which is measured with the flatness gauge) can only be observed above a certain unflatness limit, a more detailed analysis showed that at the beginning of a rolling campaign for flat strips the agreement of measured strip and calculated roll gap profile was very good. Later in the rolling campaign the deviations got bigger. This clearly indicated the deficiencies of the on-line thermal crown and wear model in operation at the hot strip mill. So the logical next step was to install new roll-state models.

Roll wear model

As part of the co-operation programme, efficient numerical methods based on Fourier transformation, and 2D finite element (FE) method in the Fourier space allow the use of a fine discretisation and the rolls (crown, taper, thermal crown, wear). The model supports various actuators such as roll bending (positive and negative), swiveling, segmented roll cooling in combination with VAI’s thermal roll crown model and roll shifting with, for example, the SmartCrown work roll contour.

In order to verify the accuracy of the model, the results have been compared (see Figure 2) with a conventional off-line 3-D FE model which shows excellent matching of the two methods. Figure 3 shows a comparison between the conventional on-line approach and the new on-line model for roll stack deflection. It is also important to note that a short calculation time for an on-line model is of great importance in order to compute correct parameters for each material. The typical calculation time using a 2GHz PC or similar computer is 50ms. All necessary calculations are automatically performed during roll change and during rolling.

Pre-study

In order to compare the actual performance of the existing process automation system with the new
voestalpine has developed a roll-wear model for the centre part of the rolls which is based on extensive automated roll measurements. Statistical analysis, based on a physical and empirical approach, produced a model with highly improved accuracy, and Figure 4 shows the comparison of measured and predicted (old and new model) centreline wear for a series of rolling campaigns and for the rolls of a specific mill stand. The much-improved accuracy can clearly be seen. The remaining deviations can, to a large extent (although not clearly quantified), be explained by the complex measurement procedure: the wear is calculated as the difference between measured roll contour after grinding and before re-grinding. Absolute reference values for the roll diameter are not available, as just a few degrees Kelvin difference in roll temperature between the two measurements cause a diameter variation of 50–100 μm. Thus, diameter measurements at both ends of the roll barrel length are used for reference, making an automatic evaluation quite difficult.

In the 10-month operation the new wear model has shown good stability of the prediction accuracy. A small offset in the average of predicted and measured wear, which may occur due to various reasons, can easily be compensated for by a simple on-line adaptation, and the standard deviation of the model error remains constant.

In order to obtain the full wear profile of a roll, the wear contribution of each individual strip has to be calculated, taking into account the actual shifting position of the work rolls and the different strip widths. All these geometrical dependences are precisely considered in VAI’s roll-wear calculation. In addition, the increased wear that is observed in the area of the strip edge is taken into account, based on a physical approach.

Figure 5 shows the comparison of calculated and measured wear profile after a rolling campaign, where the strip-edge wear effect is clearly seen. In many other cases this effect is not clearly visible in the measured wear profile because the edge wear is distributed over a wider area of the barrel length due to the strip width variation and work roll shifting. However, in comparing the measured and calculated wear profile, and by ignoring the edge effect, it is clear that the effect is present after every rolling campaign, and thus has to be carefully considered.

Figure 5 also shows the significant wear difference that may occur between top and bottom work roll. The prediction for the total centreline wear was about 10% lower than the measured wear, however, after correction the measured and calculated wear profiles match very well.

Thermal crown model In order to match the high accuracy of the roll-stack deflection model, the work-roll thermal expansion model has also been improved. In a
first step, the temperature field within the work roll is calculated for the calculation of the thermal work-roll crown then the expansion due to the temperature field is calculated (see Figure 6).

Conventional models just integrate the thermal expansion along the radius of the roll, however, by doing this for various positions along the barrel length, the thermal expansion profile is calculated. Sometimes ‘influence functions’ are used to smooth the thermal crown across the width.

The forces inside the roll caused by temperature gradients and the effect on the expansion itself are also considered. This calculation can be characterised by use of the Lamé equation, generalised for inhomogeneous temperature distribution, and semi-analytical solutions in cylindrical geometry.

Furthermore, it is very important to identify the precise heat transfer coefficients of strip/roll and roll/water, based on actual measurements. For this reason a special measuring device (see Figure 7) was used to measure the contour of the roll gap in several stands. To do this the roll gap is opened to about 5cm and the roll gap scanner moves from one end of the roll gap to the other and scans the form of the roll gap and the roll surface temperatures. Figure 8 shows the roll gap contour measured (a) after 30 strips, (b) at the end of a rolling campaign, and (c) after an additional 5 minutes of water-cooling. This picture also includes the calculated contours after parameter identification which shows a good match with the measured values. At the time of these measurements the prediction model for the edge wear was not available so there are significant deviations in the area of the strip edges. By replacing the calculated wear at the end of the rolling campaign with the measured wear, the model and measurement show an almost perfect agreement.

In-line measurements of this type have the advantage of showing the status at various positions during a rolling campaign and thus give a good impression of the dynamic behaviour of the thermal crown evolution. They are therefore very useful for adjusting the parameters of the thermal crown model. The difficulty in evaluating the measurement results is that the raw measurements show the sum of basic roll crown, thermal expansion, wear and roll deformation due to gravitation and roll balancing forces. Roll deformation especially has to be carefully taken into account using the roll stack deformation model. A further disadvantage of this type of measurement is that it is time-consuming, and thus very costly in a bottleneck plant like the voestalpine hot strip mill. For this reason, a method was developed that also allows identification of the model parameters from off-line contour and temperature measurements directly at the end of a rolling campaign.

Figure 9 shows a comparison of measured and calculated thermal crowns approximately 10 minutes after the last strip. The increased number of measurements that could now be done demonstrated that the heat transfer coefficients identified for one type of roll were not valid for another roll type or even for a roll of the same type, but from a different supplier. The reason for this could be found in the inaccuracy of thermal data (thermal conductivity of roll core and shell material) supplied by the roll manufacturers. After obtaining more precise data and making them consistent for different roll types and suppliers, the thermal crown prediction is now very accurate, as systematic verification measurements demonstrate.

FIRST RESULTS OF THE NEW MODELS

After tuning, the new thermal crown and wear models were used as an input to the existing profile and flatness setup and control system. The resulting improvement in the profile control (reduction of profile tolerance
violations) clearly proved the results of the pre-study regarding the performance of the previous thermal crown and wear models.

Figure 10 shows the (bi-monthly evaluated) percentage of strips with profile tolerance violation. In period 1 (up to end of May 2003), the old thermal crown and wear models were active. Period 2 is where the new models were already active, but the thermal properties of the rolls were not completely adjusted. In period 3, the fully adjusted new models are active. The figure clearly shows the big improvement in profile accuracy achieved.

PROFILE AND FLATNESS STRATEGY

The aim of the profile and flatness strategy is to establish a certain roll gap shape for each stand by use of the roll gap actuators (work roll bending and shifting with or without SmartCrown). The roll gap shape is calculated taking into consideration the material cross flow, which is high in the first stands of the finishing mill and close to zero in the last stands. For the calculation of the best profile and flatness setup, a cost function optimisation formulation of the problem is chosen, using a powerful mathematical algorithm. The advantage of the mathematical optimisation approach is that it is relatively simple to handle different types of restrictions for the setup values for shifting positions and bending forces of the seven finishing stands. The types of restrictions considered include:

- Absolute shifting position limitation due to actuator limits and product specific limitations
- Limitation in 'effective crown' difference due to work roll shifting between subsequent stands. This type of restriction is required in the old setup model and is considered in the new model to allow for a smooth transition from old to new. The expectation is that after commissioning this type of restriction will no longer be required in the new model.
- Roll shifting limitation between subsequent strips due to limited shifting speed and gap time between strips
- Shifting limitations between subsequent strips to avoid contour defects due to thermal crown edge
- Inactive stands or fixed shifting positions
- Absolute bending force limitations due to actuator limits and considering required in-bar control range
- Limitation of inter-stand unflatness

In preprocessing, these different restrictions can be condensed (e.g., shifting limitations between subsequent strips result in absolute shifting position limitations during setup calculation). Nevertheless, in total, 56 restrictions have to be taken into account for the 14 setup parameters (position and bending force for each of the seven stands). In certain cases, these restrictions may even be incompatible with each other. In this case, a clear concept is required to find out the contradicting restrictions and to resolve the problem following a clear priority concept.

The new setup strategy is finished, and its commissioning will start in summer 2005, after the adaptation of the profile and flatness model is in operation. Because the objective is to try to go as far as possible with physical modelling, the remaining error in profile prediction is very low compared to other models. Nevertheless, some adaptation will be required. Currently studies on the nature and behaviour of the remaining deviations are done in order to define a problem-specific adaptation technology.

Finally, a closed loop flatness control based on the results of the flatness gauge will be implemented in the level 1 automation systems of the finishing mill. The control parameters for this controller will be specifically calculated and supplied by the new models for each strip.

OUTLOOK

An accurate model is required to calculate the precise influence of the various effects and actuators on roll gap shape. Optimised control gains make feed-forward and closed loop profile and flatness control more efficient. In addition, roll stack deflection also significantly contributes to the total mill stretch. With the new approach it should therefore also be possible to improve head end thickness performance, even for the first strip of a rolling sequence.

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