New dimensions in precision and calculation speed of cold-rolling-online-models

FEM based pass-schedule-calculation with GPU for the future challenges of thin, high-strength materials

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Abstract

Due to calculation speed requirements for online-models in cold-rolling, significant simplifications in mathematical modelling have been used so far.

Since many years, pa-innovations GmbH in cooperation with Mathweis Engineering GmbH and allpccloud GmbH, have been developing high-performance rolling models and Level 2 systems. Within the scope of this cooperation an innovative concept was created, which applies the required scientific depth within the finite element method through high calculation power of modern GPUs (graphic processing units).

Currently, in cooperation with Salzgitter Flachstahl GmbH as a longtime partner, the model core modernisation of the cold rolling tandem mill is carried out, based on this development.

Figure 1: The 5-stand cold tandem mill of Salzgitter Flachstahl GmbH.

Via this modernisation, the mill will be adjusted to the ongoing progression of product range. In particular, increasingly thinner, high and highest-strength flat steel products require a considerable extent of process-technological accuracy of modelling in order to meet the increased quality needs of customers. Additionally, the plant availability will be increased and the set-up time as well as the rework rate decreased. Furthermore, the plant limits are going to be calculated more precisely and the required time for product development can be further reduced. Further targets are increased user-friendliness and process transparency, while the system maintenance effort decreases.

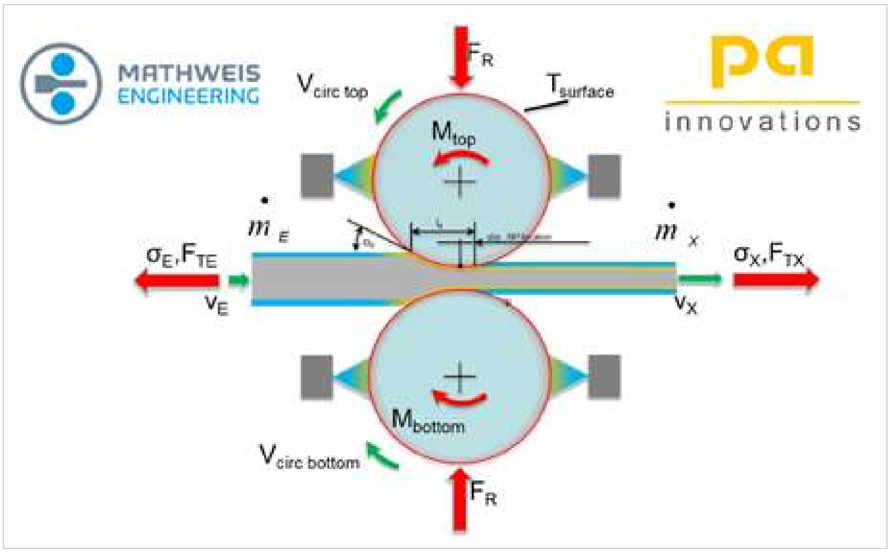

Figure 2: Depiction of forming technology parameters in cold-rolling

Motivation

In the area of cold rolling, there is a tendency towards higher strength in combination with lower final thickness. The model requirements are a precise knowledge and suitable handling of cold rolling limits for these products. On the one hand it is necessary to provide sufficient precise calculations of force and work prediction.

On the other hand, a reliable prediction of stability criteria such as forward slip and neutral point position, requires the knowledge of tribological and mechanical boundary conditions in the roll gap (Figure 2).

Classical online-cold-rolling models as part of modern process control systems (level 2) for cold rolling applica-

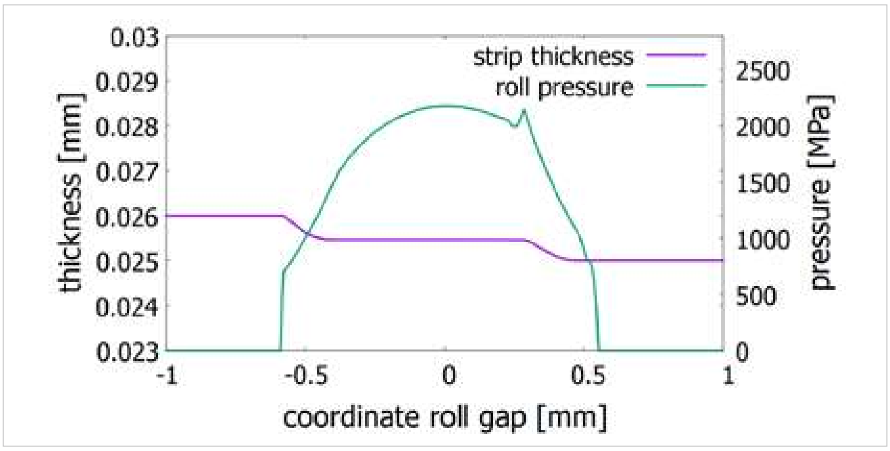

Figure 3: Thickness and pressure distribution in the roll gap with distinct transportation zone

tions usually apply the Bland-Ford-Ellis approach in the metal-forming-theory, as well as the Hitchcock roll flattening theory.

As a well-known fact in rolling theory, these approaches cannot provide sufficient precise results to build up the limit range of cold rolling (e.g., thin, high strength).

The flattening theory following Hitchcock assumes a circular arc work-roll-contour in the roll gap. However, this assumption is not always applicable, especially for the rolling of high-strength materials at low final thickness, as well as skin pass rolling.

The necessary scientific depth for the elastic-plastic-modelling is feasible by modern finite elements methods.

So far, a major limitation for the online application of such models was the long computation time, which is overcome by a new development based on GPU-computing.

GPUs are high-performance, trend-setting graphics processors with a multitude of computation cores.

The presented mathematical model is based on the stripe theory [H. Pawelski, O. Pawelski, "Technische Plastomechnaik", Stahleisen 2000]. According to this theory, the rolled material is conceptually divided into infinitesimal small stripes in longitudinal direction. It is assumed that the shaping (compression in vertical direction), which the stripe is exposed to throughout the roll gap, remains plane and proceeds homogeneously over the thickness. This assumption is considered as valid up to a 1/3 ratio of thickness / compressed length (l_d in Figure 2).

In the classical theory, assuming a fully plastic material behaviour, the well-known equations for strip longitudinal tension and rolling pressure are yielded:

$$b\,\frac{d\sigma_x}{dx} + (\sigma_x + p)\frac{db}{dx} + q = 0,\ \sigma_x + p = k_f \text{ and}$$

$$q = \mu p$$

with half-strip-thickness b, longitudinal tension σx, rolling pressure p, friction coefficient μ and friction stress q. The solution of this equation is the distribution of the roll pressure $p(x)$ in the roll gap.

It is required to know the elastic flattening of the work rolls sufficiently, in order to have a reliable prediction of the pressure distribution. The rolled material may not get reduced continuously in the roll gap [N.A. Fleck, K.L. Johnson, „Cold rolling of foil", IMechE 1992]. On the contrary it is possible, that transportation zones with constant strip thickness are formed (Figure 3). These zones grow, as the strip thickness gets smaller and thus the roll separating force increases (but not the rolling torque). This effect limits the achievable final thickness, and is particularly relevant for foil rolling, but can also occur in different situations, for example at large work roll diameters or high friction.

Realisation of the model with FEM and GPU

The newly developed roll separating force and rolling torque prediction model presupposes an elastic behaviour of the work rolls with spatially resolved elastic deformation. It also considers validity of the stripe theory at elastic-plastic material behaviour of the strip. The mechanical problem is solved via a nonlinear finite element method (FEM). In order to fulfil the requirements of calculation time for an online application, a graphics processing unit (GPU) is used (e.g., NVIDIA A40).

The Newton-Raphson-method is used as solving algorithm for this class of non-linear mechanical problems [K.-J. Bathe, „Finite-Elemente-Methoden", Springer 1990]. In this method the mechanical equilibrium $R - F_{(u)} = \Delta_{res}$ is set up with the vectors of the external forces R and the internal nodal forces $F_{(u)}$. The vector of the nodal displacements is iterated such that Δ_{res} vanishes i.e., $R - F_{(u)} = 0$. The relation between F and u maps the nonlinearities in the system, which means plastic material behaviour, contact length and material transport. After the iteration of the equilibrium

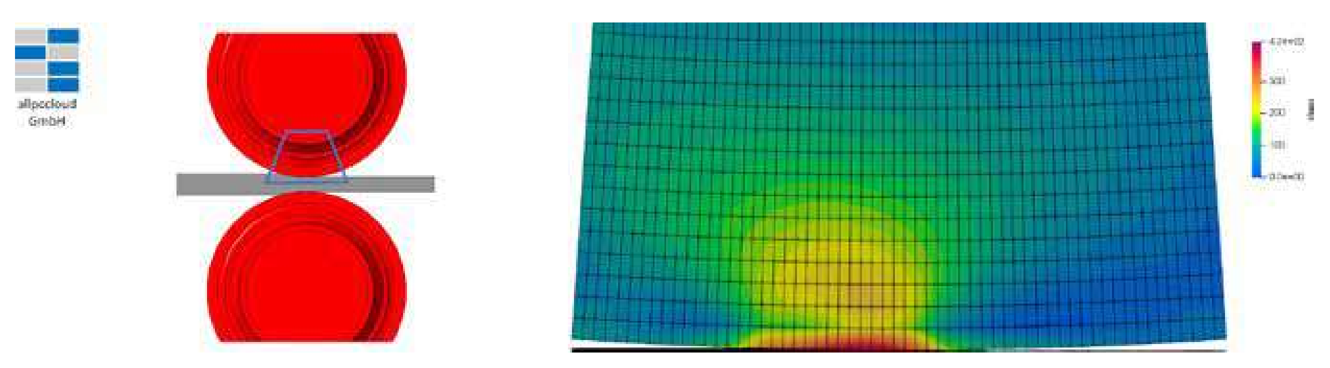

Figure 4: Example of a stress distribution in work roll and strip (von Mises stress; two-dimensional contact model with symmetry level in strip-thickness-direction)

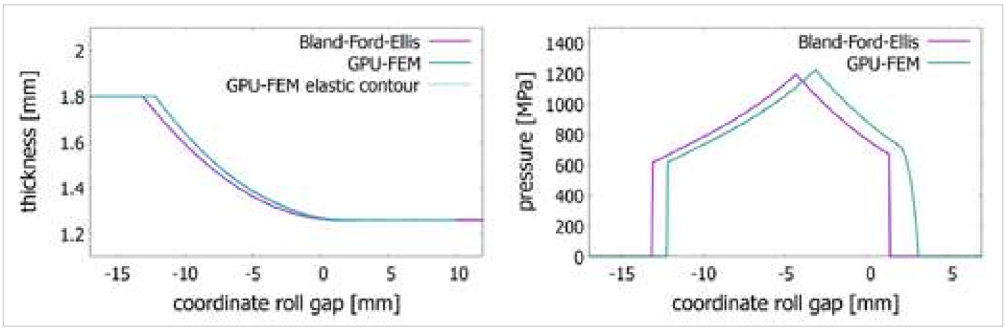

Figure 5: Thickness- (left) and pressure-distribution (right) in the roll gap of mill stand 1, comparison of the results of the classical theory (Bland-Ford-Ellis) and FEM. Clearly observable is the portion of the elastic decompression at the roll gap exit, which is not considered in the classical theory. The resulting increased compressed length leads to a higher roll separating force.

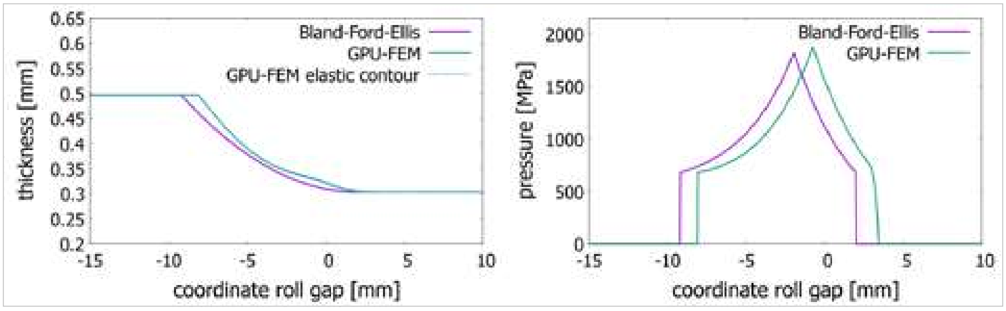

Figure 6: Thickness- (left) and pressure-distribution (right) in the roll gap of mill stand 4, comparison of the results of the classical theory (Bland-Ford-Ellis) and FEM. The thickness distribution of the FEM result indicates the formation of a transportation zone. This effect is not covered by the classical theory.

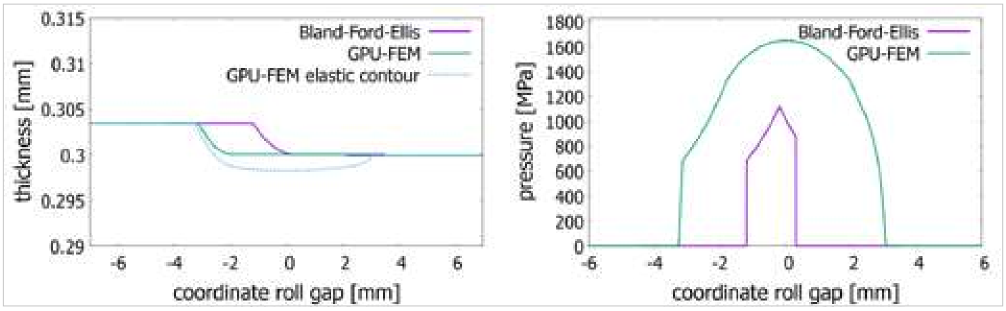

Figure 7: Thickness- (left) and pressure-distribution (right) in the roll gap of mill stand 5, comparison of the results of the classical theory (Bland-Ford-Ellis) and FEM. Clearly observable is that the elastic part dominates the pressure-distribution (refer also the dashed curve in the thickness-distribution).

cycles, the resulting roll separating force and rolling torque are calculated.

A sector of the work roll is meshed with isoparametric quad elements in radial and tangential direction (Figure 4). A linear-elastic material behaviour, a state of plane strain (2-D) and symmetry in strip thickness direction is assumed. The inner degrees of freedom of the work roll are eliminated in a pre-processing step by means of static condensation, which reduces the complexity of the problem significantly. In the displacement vector u only the spatially resolved nodes of the roll surface remain.

The rolled strip is meshed by quad elements as well, but with an additional subgrid approach, which increases the spatial resolution of the thickness and pressure distribution while not increasing the size of the vectors R, F, u and the associated stiffness matrix.

The resulting exit thickness does not meet the target value without compensating the elastic flattening of the work roll. Thus, the set roll gap must be corrected based on the results by means of an iteration. This corrected gap value yields valuable information to consider possible roll to roll contact next to the strip (roll-kissing i.e., roll separating force is only partially applied on the material).

Comparison of model calculations following the classical and new method

For comparison an example of a 5 stand tandem mill with following data is used: Entry thickness = 1,8 mm; exit thickness = 0,3 mm; yield stress from 500 to 900 N/mm²; coefficient of friction G1= 0,061; G4= 0,037; G5= 0,075; work roll diameter G1 = 510 mm; G4 = 540 mm; G5 = 445 mm.

The results for the mill stands 1, 4 and 5 are presented in Figure 5 to Figure 7 in comparison to the results of the classical theory.

In the automation application, the process parameters (yield stress curves and friction coefficient curves) are adjusted by adaptation, such that the measured values of roll separating force and rolling torque can be predicted as precisely as possible. Since the classical model does not consider the elastic component of the strip deformation, the roll separating force is underestimated, while the elastic zone does not contribute to the rolling torque. This leads to physically implausible values of the adapted process parameters in the classical model, which inevitably causes errors in the pre calculation of similar or new material types.

Outlook

The new calculation method not only delivers a significantly more precise prediction of roll separating force, rolling torque and slip, but also provides a completely new quality of the basis for adaptation of the yield stress curves and friction coefficient curves due to measured process data. These adapted process data remain physically plausible, in comparison to the classical theory. The described method can be used for the efficient introduction of new materials, an effective skidding monitoring already at the pass-schedule calculation, as well as for a detailed pre-calculation of shear rolling effects (e.g., ski-formation). Topics, which are of great importance for the practical rolling process.