Laminação
Rolling
49º Seminário de Laminação - Processos e Produtos Laminados e Revestidos
49th Rolling Seminar - Processes, Rolled and Coated Products
ISSN 1983-4764

TRIPLE-A: HIGH SOPHISTICATED ROLLING MODEL WITH SPECIAL EMPHASIS ON ROLLING CONDITIONS IN THE FINAL PASS OF COLD AND TEMPER ROLLING MILLS[1]

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Abstract

The final pass any cold rolling mill is typically characterized by reduced relative and absolute strip thickness reduction, small strip thickness, raised material strength due to work-hardening in the previous deformation steps, often in combination with application of rough work rolls (to adjust the strip surface topology). These process conditions can lead to severe work roll flattening and in extreme cases to practical limitations of the reduction capability and the achievable final product thickness (rollability). The (theoretical) rollability limit is reached if the strip thickness does not decrease anymore although the work rolls are adjusted more and more against each other resulting in extreme work roll flattening. Siemens VAI's TRIPLE-A cold rolling model was developed for offline calculations in order to predict rolling forces and rolling torques very accurately over a wide range of applications covering the trend to very thin and hard strips as well as rolling scenarios in the final pass of any kind of cold rolling and temper rolling mill. The new high sophisticated simulation model ensures an improved modeling of rolling, as the circumferential work roll displacements allow for the existence of slip- as well as no-slip-zones inside the roll bite. The formation of a neutral zone, where the roll tangential speed matches the strip speed, instead of a neutral point is a consequence of this approach. Furthermore, the model offers the big benefit that the "rollability" and reduction capability can be determined very accurately compared to existing cold rolling models. Triple-A was calibrated against practical data from industrial cold rolling mills. Excellent agreement between measured and predicted rolling forces and rolling torques prove the validity and quality of the developed model. Therefore Triple-A represents a strongly improved tool for the dimensioning of cold rolling mills.

Key words: Cold rolling; Temper and skin-pass rolling; Mathematical model; Rollability; Cold rolling limits; Last rolling pass.

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[1] *Technical contribution to the 49th Rolling Seminar – Processes, Rolled and Coated Products, October, 22nd-25th, 2012, Vila Velha, ES, Brazil.*

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1 INTRODUCTION

The final pass of a tandem cold mill (TCM), reversing cold mill (RCM), double cold reduction mill (DCR) or double stand skin pass mill (SPM) is typically characterized by reduced relative and absolute strip thickness reduction, small strip thickness, raised material strength due to work-hardening in the previous deformation steps, often in combination with application of rough work rolls (to adjust the strip surface topology). These process conditions can lead to severe work roll flattening and in extreme cases to practical limitations of the reduction capability and the achievable final product thickness (rollability).

If we consider rollability (aptitude for rolling), we have to distinguish in a first step between practical and theoretical rollability. The “theoretical rollability limit” is reached if the strip thickness does not decrease anymore although the work rolls are adjusted more and more against each other resulting in extreme work roll flattening (cf. Figure 1). This case is comparable to the border case of “kissing work rolls” (absence of strip between the work rolls) where the applied force from the roll-gap adjustment cylinders is purely converted into elastic deformation of the work rolls. In reality, however, the rollability limit for certain products is frequently reached before the "theoretical rollability limit", which is due to limitations regarding installed rolling forces and mill power (respectively motor torque) and technological constraints (e.g. maximum allowed draft to ensure that no slippage occurs between work roll and strip or limited rolling forces to prevent flatness defects). The latter limits are designated as “practical rollability limits” in this article.

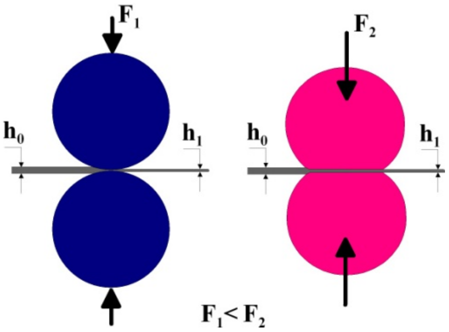

Figure 1: Illustration of the case of theoretical non-rollability.

The physical reason for the extreme work roll flattening in such rolling cases is, that the work roll surface tends more and more to a concave shape, the “sharper” a surface load becomes (cf. Figure 2). With respect to rolling processes, this means that the work roll does not permit “sharp edge loads” (due to very short contact lengths) with a convex contour, but switches to extreme flattening with an enlarged contact length.

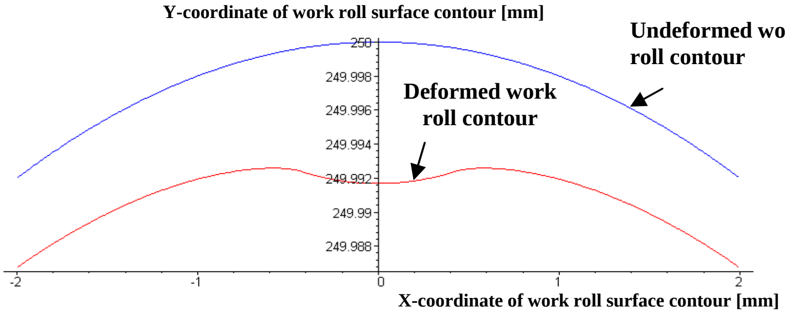

Figure 2: Concave (deformed) work roll contour.

Figure 3 illustrates a typical example of a deformed work roll contour and the underlying calculated contact pressure distribution (between work roll and strip) considering a final pass of an industrial DCR mill.

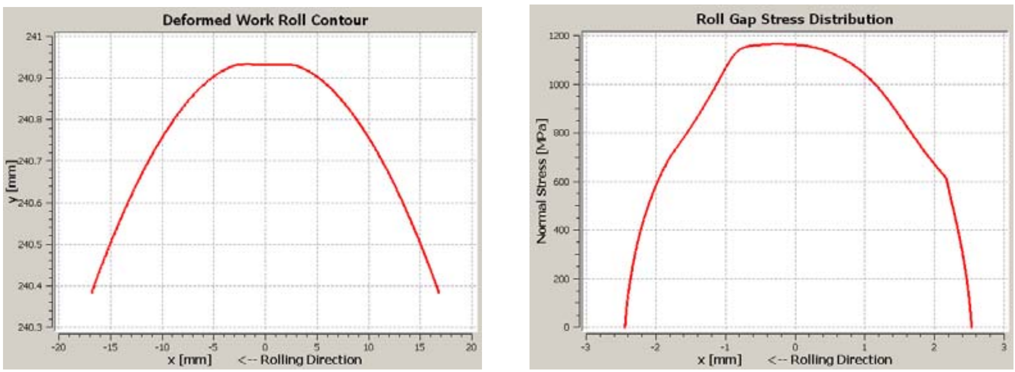

Figure 3: Deformed work roll contour and roll-gap contact pressure distribution considering the second pass of a DCR mill

Classical cold rolling models, e.g. based on the theories of Stone [1], Bland and Ford [2] or Orowan [3], use amongst others the simplifying assumptions of a constant coefficient of friction inside the roll bite and a circular arc work roll deformation which lead in case of the final rolling pass frequently to inaccurate and useless calculation results or to significant convergence troubles of the underlying calculation algorithm. These models are using either an enlarged circular-arc work roll radius (constant radius of curvature) to model the elastic work roll flattening by Hitchcock [4] or even neglect the work roll deformation (rigid work roll).

Our new TRIPLE-A cold rolling model was developed for offline calculations in order to predict rolling forces and rolling torques very accurately over a wide range of applications covering the trend to very thin and hard strips as well as rolling scenarios in the final pass of any kind of cold rolling and temper rolling mill. Offline models for the simulation of cold and temper rolling primarily serve as dimensioning tools for the optimization of rolling processes and mills in terms of force and power requirements, throughput and strip quality. For this purpose, FEM (Finite Element Method) models based on commercial multi-purpose software packages are unacceptable due to their extensive calculation costs. Therefore, tailor-made, highly specialized mathematical models with drastically lower calculation efforts are essential.

The new high sophisticated simulation model ensures an improved modeling of rolling, as the circumferential work roll displacements allow for the existence of slip- as well as no-slip-zones inside the roll bite. The formation of a neutral zone, where the roll tangential speed matches the strip speed, instead of a neutral point is a consequence of this approach. Furthermore, the model offers the big benefit that the "rollability" and reduction capability can be determined very accurately compared to existing cold rolling models.

2 THE TRIPLE-A ROLLING MODEL

Siemens VAI's "**Advanced Arbitrary Arc**"-Model (Triple-A) is based on a non-circular arc theory for the calculation of the elastic work roll flattening. In addition to the radial displacements of the work roll surface, also its circumferential displacements, generated mainly by the acting shear stresses between work roll and strip, are taken into account. The circumferential work roll displacements heavily affect the relative speed (slip speed) between the surfaces of the deformed work roll and the strip and consequently, the evolution of frictional forces is re-affected by the circumferential displacements. The effect of circumferential displacements becomes more and more crucial with decreasing strip thickness and draft in combination with increasing "macroscopic" friction (e.g. in case of rough work rolls) between work roll and strip. The formation of a neutral "no-slip" zone instead of a neutral point is a consequence of this approach.
The underlying rate-dependent elasto-plastic model of the strip in Triple-A is based on von Karman's theory [5]. However, several extensions have been added, including an elastic compression zone at roll gap entry, an elastic recovery zone at roll gap exit and possible plastic zones in between, considering also internal elastic zones between plastic zones (cf. Figure 4). Therefore, the case of "contained plastic flow" [6]– known from thin strip and foil rolling - will appear automatically without imposing additional simplifying assumptions.

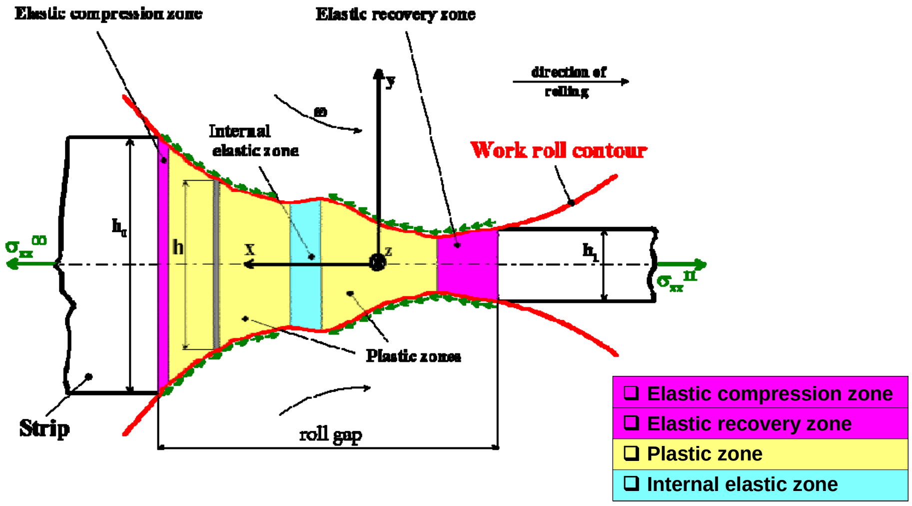

Figure 4: Strip segment model with elasto-plastic theory.

The algorithm for the determination of contact between work roll and strip is based on an iterative procedure: The contact stresses (compressive and shear stresses) are calculated for a given distribution of strip thickness and slip speed on the strip's surface. The resulting contact stresses are applied to the work roll surface. This in turn yields a new deformation and speed state of the work roll surface, which serves as input for the next iteration step.
In a first attempt, the resulting contact pressure is calculated keeping the strip's thickness reduction constant. In order to ensure the prescribed draft, the work roll centre has to be adjusted during the iteration scheme according to the resulting work roll deformation from the previous step. This method offers the big advantage that

rollability can be evaluated there from: If the strip exit thickness h_1^{eff} does not decrease any further in the course of the iterations, although the work roll centre is adjusted more and more to the strip, then “non-rollability”, respectively the theoretical rollability limit is detected (cf. Figure 5). h_1 in Figure 5 designates the target exit thickness of the strip.

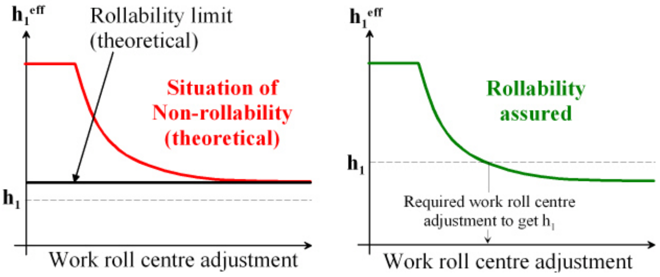

Figure 5: Detection of (theoretical) non-rollability (left) and rollability (right).

A big benefit of Triple-A is that the calculation can be continued up to and beyond the practical and even the theoretical rollability limits. Therefore, Triple-A represents a strongly improved tool for the layout, design and optimization of cold rolling mills.
The comparison of simulation results from Siemens VAI’s Triple-A Model with results from FEM-simulations shows indeed excellent agreement. In case of extreme rolling conditions (e.g. in the final pass of a TCM), the results of a classical rolling model based on a circular arc cold rolling model are far away from the Triple-A model as well as from the FEM simulation results (cf. Figure 6 and Table 1).

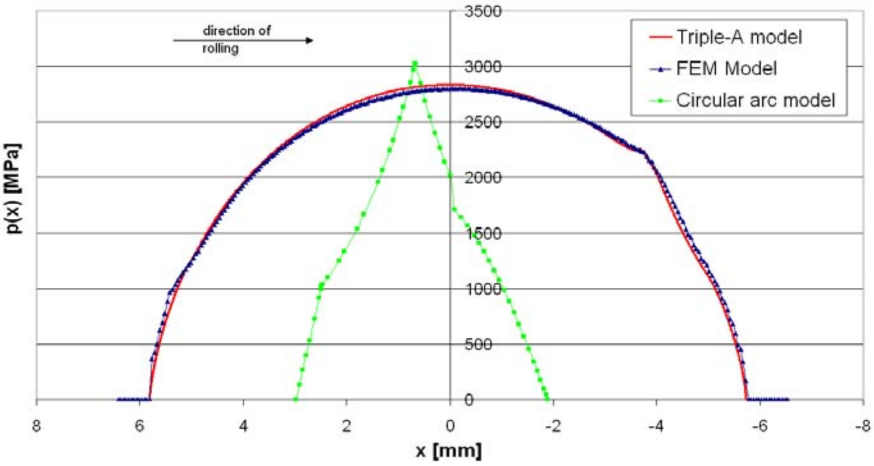

Figure 6: Calculated contact pressure distribution inside the roll bite.

Table 1: Comparison of calculation results

	Circular Arc Model	Triple-A	FEM
Specific rolling force [kN/mm]	7.27	24.89	24.93
Projected contact length [mm]	4.87	11.55	11.56
R’/R [1]	5.61	-	-

Triple-A was calibrated against practical data from industrial cold rolling mills. Excellent agreement between measured and predicted rolling forces and rolling torques prove the validity and quality of the developed model. Figure 7 illustrates a comparison of predicted and measured rolling forces in case of a skin pass mill considering different steel grades, strip thicknesses, strip tensions and mill speeds.

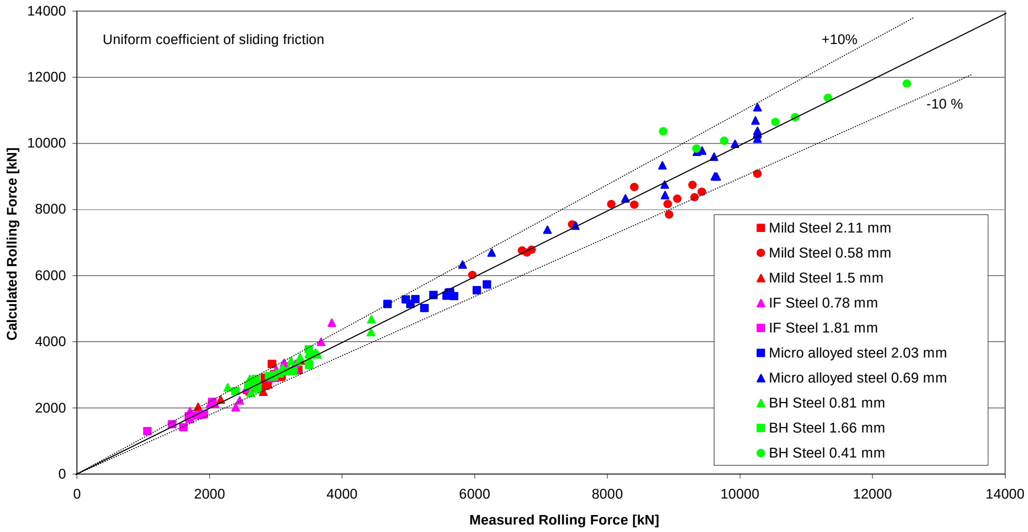

Figure 7: Comparison of predicted and measured rolling forces for different steel grades and different strip thicknesses using a uniform coefficient of macroscopic sliding friction.

3 CONCLUSION

- Classical cold rolling models (circular arc) are not adequate for
  - Evaluation of rollability
  - Modeling of cold and temper rolling processes with hard and thin strips (in combination with small reductions and high friction)

Siemens VAI's Triple-A Cold and Temper Rolling Model features
  - Elastic work roll deformation incl. circumferential displacements
  - Strip segment model with rate-dependent elasto-plastic theory
  - Self-adjustment of "contained plastic flow"
  - Regularized Coulomb friction law allows existence of no-slip zones
  - Calculation can be continued up to and beyond the practical and even the theoretical rollability limits
  - Excellent agreement between results from Triple-A and FEM

Therefore Triple-A represents a strongly improved tool for the dimensioning of cold rolling mills.

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