A three-dimensional finite element model for the roll bending of heavy plates using a 4-roll plate bending machine

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1 Introduction

Roll bending is a manufacturing process in which sheet metal is continuously formed into a round shape with the help of typically three or four rotating rolls. It is used in particular for the production of thick-walled pipes and shells with large volumes, which are used in the maritime sector, in pipeline construction and in the field of renewable energies. In these areas, at the current state of the art, the process is mainly controlled manually. However, the control of the process is of great importance for its efficiency. For example, over-controlling the machine leads to over-bending of the plate and thus often to material waste, whereas under-bending requires additional rolling passes and leads to an increase in production time. To reduce the human influence on the economic efficiency of the process and to objectify the process, research is currently being carried out on the development of automation solutions for roll bending.

A major challenge regarding the automated control of roll bending are batch-specific fluctuations of the material properties of the plates, such as thickness, strength or residual stresses. During the control of the process, the influence of these fluctuations on the forming result has to be determined and compensated by an adequate adjustment of the roll positions. To develop technical solutions for this, a high level of process understanding is required. However, the mechanisms that take place during roll bending have not been fully understood and described [1]. For this reason, in recent years more and more studies have focused on modelling roll bending by using the FEM, as this allows to investigate the development of process variables such as the plastic deformation in the contact zone in detail.

In this paper, a computationally efficient three-dimensional FE model is presented that can be used for the analysis of roll bending. With the help of the model, a sensitivity analysis was carried out and the influence of workpiece and machine parameters on the forming result was investigated. The aim of this study is to contribute to an increased understanding of the process by highlighting significant and negligible influencing variables on the forming behaviour of a plate. It should be emphasised that within the framework of the FE analysis, the influence of residual stresses was investigated, which, to the authors' knowledge, had not been considered in previous FE models for roll bending. In addition, the FE model developed in this work differs from previously published models because in this model the forming process was divided into individual sub-steps and modelled as a process chain. A separate model was created for each process step and the transfer of the stress and deformation state of the plate was realised using a Dynain-file.

2 State of the art in numerical simulation of roll bending

Some analytical models have already been developed for roll bending, but due to oversimplifications they cannot fully describe the forming process [1]. For this reason, the finite element method has been increasingly used in the past to investigate the forming process in more detail. In this context, trends in modelling have emerged, which will be briefly described in the following.

From the FEM point of view, the modelling of roll bending is a complex task. Due to the large movements of rolls and plate as well as the plastic deformation of the plate, both geometric and material non-linearities occur. In addition, there is non-linearity due to the frictional contact between the rolls and the plate, by which the feed of the plate is generated. Due to these nonlinearities, very small time steps are required in the calculation, so instead of implicit time integration, explicit time integration has been used in most works [1–7]. In the few papers where implicit time integration was chosen, the process was geometrically simplified to a 2D problem in order to reduce the computation time [1, 8].

Regarding the modelling of the rolls, the assumption of rigid bodies is state of the art [2–8], which is justified due to the high strength of the roll material compared to the plate material [8]. Furthermore, the support of the rolls is assumed to be rigid [1–8], which is probably due to the lack of knowledge of the stiffness of the roll support. For modelling the plate material, the simplified assumption of isotropic elastoplastic material behaviour is state of the art [1–8], whereas its strength is anisotropic in reality [9].

Residual stresses in the plate material have, to the authors' knowledge, not yet been considered in the models published so far.
In the previous FE studies on roll bending, different investigation objectives were pursued. One important aspect was the determination of process forces for the design of roll bending machines [5]. Furthermore, the FEM was used to validate analytical models and to establish an approximate relationship between the roll feed and the resulting plate curvature [1, 4, 6]. Zhao et al. have made an important contribution to the understanding of elastic springback in roll bending by investigating its spatial and temporal evolution in 3-roll roll bending and were able to show that springback already occurs in the impact zone of the roll bending machine [8]. Zeng et al. have investigated the influence of various machine-side parameters in 3-roll roll bending with conical rolls on the geometrical accuracy of the manufactured cones [2]. To the authors' knowledge, a comprehensive sensitivity analysis to investigate the influence of both machine-side and workpiece-side influences on the forming result, from which the relative importance of the various influencing variables can be derived, has not yet been published. This is therefore the aim of the present study.

3 Model setup in LS-DYNA

The FE model for roll bending is built using the software LS-DYNA. In the following section, the relevant model properties are explained.

3.1 Modelled plate bending machine

The modelled plate bending machine was a 4-roll plate bending machine of the type W12-60*4000 from the Chinese manufacturer Nantong Shengli Heavy Machine Manufacturing (Fig. 1). This machine feeds the side rolls along a circular path. To generate the plate feed, the centric rolls can be driven in rotation. The dimensions of the plate bending machine were determined using a 3D scanner.

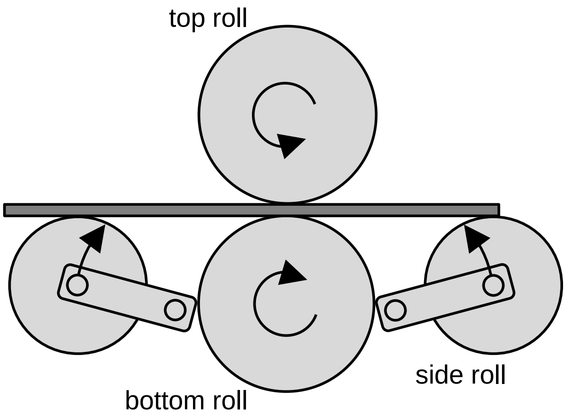

Fig.1: Modelled 4-roll plate bending machine.

3.2 Modeling of the process as a process-chain

The typical process sequence for roll bending of heavy plates with a 4-roll plate bending machine is shown in Fig. 2. At the beginning of the process, the plate is aligned by feeding it to a side roll until it reaches the stop (1). Then the plate is rolled back and one end of the plate is bent by lifting the other side roll (2, 3). This side roll is then moved back to its starting position and the plate is rolled through to the second end so that the second end can be bent (4, 5, 6, 7). After both ends have been bent, both side rolls are lifted and the plate is continuously rolled over its entire length (8).

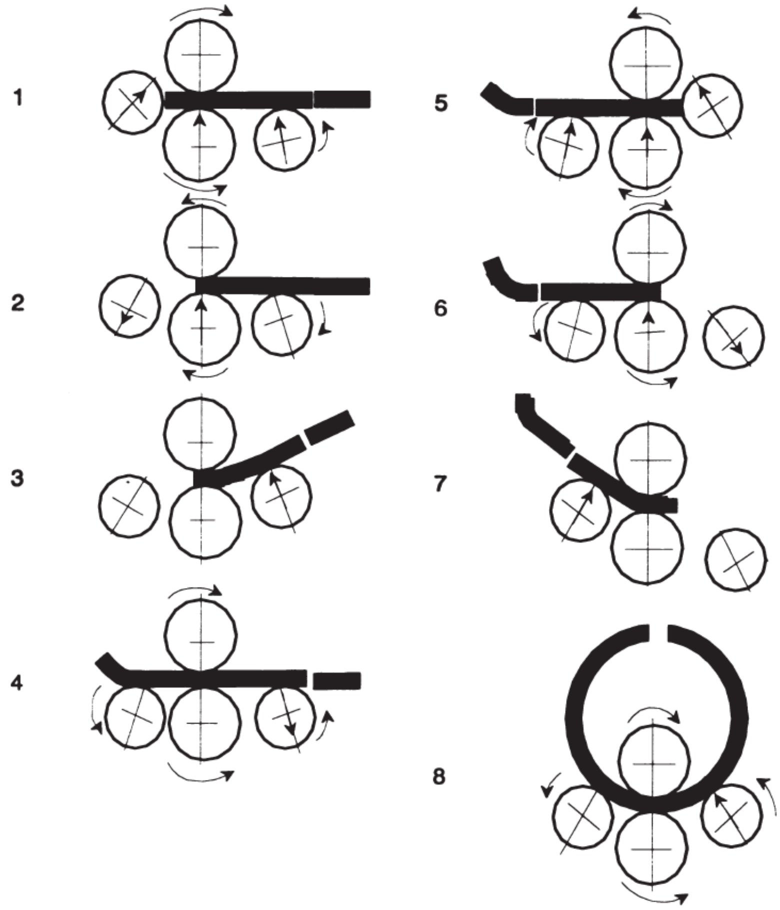

Fig.2: Operational sequence for thick plate bending process with a 4-roll plate bending machine [10].

To simulate the process sequence shown in Fig. 2 as well as similar process sequences as efficient as possible, the process was divided into individual process steps and a separate model was created for each step:

- **Bending**: In this process step, one or both side rolls are lifted, whereby the plate is formed locally. The upper and lower rolls remain stationary.
- **Rolling**: Here, all rolls have a fixed position. The top and bottom rolls are rotationally driven to generate the feed of the plate.
- **Elastic springback**: This process step takes place after the forming process, when the side rolls have been moved back. It involves the (partial) release of elastically stored deformation energy. As boundary conditions, the degrees of freedom of the plate nodes at a long edge of one end are locked and the gravitational effect on the plate is deactivated.

For modelling these process steps, different time integration methods were used. Due to the existing non-linearities and the associated requirement for small time steps, rolling was calculated with explicit time integration. Here, the circumferential speed of the rolls was artificially increased to 2000 mm/s to reduce the simulation time. For bending, the use of explicit time integration with increased infeed speed of the side rolls led to considerable dynamic effects resulting in the plate lifting off of the roll. For this reason, bending and elastic springback were calculated statically with implicit time integration and thus dynamic effects were neglected.

After the simulation of a step, a dynain file is produced, which contains the relevant information of the plate state, such as the stress and deformation state, and serves as input for the next process step. To enable the practical simulation of different process sequences with the help of the model, the models of the individual process steps were set up parametrically. A Python program was written, which can be used to automatically parameterise the models based on a predefined forming plan. This also ensures that consistent boundary conditions exist between the individual simulations of a process chain. As an example, that the positions of the rolls are matched to each other.

3.3 Modeling of the rolls and the contact

The rolls were idealised as rigid cylindrical bodies and thereby their elasticity and ballness were neglected. Taking advantage of their symmetry to the longitudinal axis, only one half of their geometry was modelled.
For the explicit time integration in the rolling process step, the rolls were modelled through contact entities using the keyword **`*CONTACT_ENTITY`**, which are based on a computationally efficient analytical description of the geometry. A constant coefficient of static friction of 0.15 was assumed for the contact between rolls and plate. The rotation of the upper and lower rolls was realised using velocity boundary conditions.
Since contact entities can only be used with explicit time integration, in the bending step with implicit time integration, the rolls were modelled by rigid shell elements. Here, the model **`*FORMING_SURFACE_TO_SURFACE_MORTAR`** was used as contact model. To reduce the computational effort in this process step, the rotation of the side rolls was disabled and the static friction coefficient in their contact model was set to 0. This reduced the contact formation with the plate to a small area, so that the side rolls did not have to be meshed over their entire circumference, but only a section on the side facing the plate (Fig. 3). The circular infeed movements were realised using displacement boundary conditions. As shown in Fig. 3, from the upper and lower rolls also only one section was modelled. However, rotation and static friction were not neglected for these rolls.
Independent of the process step, the support of all rolls was idealised to be rigid. An exception was the vertical support of the bottom roll. In this direction, in order to be able to model the compliance of the real plate bending machine, the bottom roll was supported by a spring. The stiffness of this spring was estimated approximately from the manufacturer's data on the forming capacity of the machine.

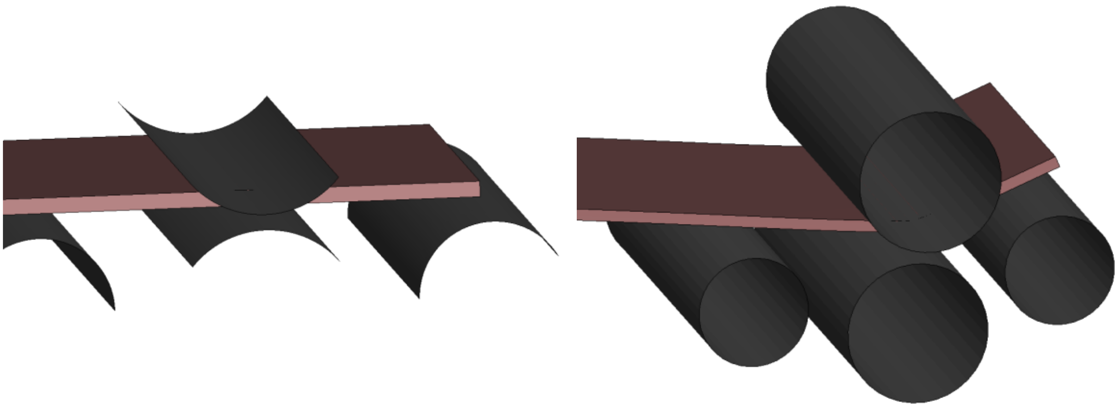

Fig.3: Modelling of the rolls by rigid shells in the bending step (left) and contact entities in the rolling step (right).

3.4 Modeling of the plate

Linear hexahedral elements (**`ELFORM 1`**) were used for modelling the plate, as these allow efficient calculation with explicit time integration [11]. The element size was chosen based on a convergence study. In the longitudinal and width direction, the elements had an edge length of 10 mm. In the thickness direction, the element edge length was adapted to the plate thickness, so that the discretisation was always carried out with five elements. This ensured the presence of an integration point in the neutral fibre. Analogous to the rolls, a symmetry boundary condition was assumed for the plate in the width direction, whereby only one half of its geometry had to be modelled.
The considered plate materials were the steels S355 and S690. For these, a Young's modulus of 207 GPa, a Poisson's ratio of 0.3 and a density of 7850 kg/m³ were uniformly assumed. As a material model the model **`*024-PIECEWISE_LINEAR_PLASTICITY ("*MAT_024")`** was used, which is suitable for the modeling of simplified elasto-plastic behaviour of metals. For the materials considered, the flow curves shown in Fig. 4 were assumed, which were determined experimentally and extrapolated for large strains using the exponential approach by Hockett-Sherby [12]. The yield-point elongation was neglected here.

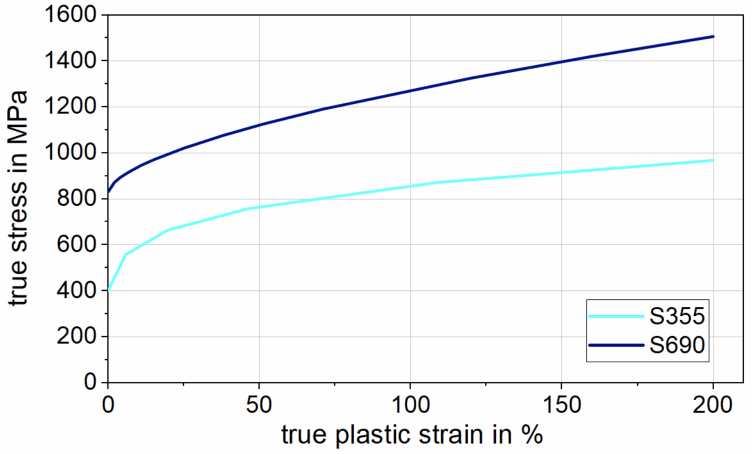

Fig.4: Flow curves of the investigated materials.

3.5 Implementation of residual stresses

To investigate the influence of residual stresses present in the plate at the beginning of a forming sequence, the keyword **`*INITIAL_STRESS_SOLID`** was used. With this keyword, an initial stress state is assigned to each element at the first bending step. Since the plates used in roll bending are often thermomechanically rolled, the residual stress state of such plates was implemented in the model. To determine a characteristic residual stress state for this, work founrd in the literature was used as a reference.

In [13], the contour method was used to determine a mapping of the longitudinal residual stresses over the cross-section of a thermomechanically rolled plate of a HSLA-100 steel. Based on the mapping, the stresses were averaged over the width, whereby a curve of the average longitudinal residual stresses as a function of the edge distance was obtained. This curve was adapted in the present work for implementation in the FE model (Fig 5, left). The curve was rescaled using the yield strength of the materials investigated, divided into equidistant sections and averaged in each of these to obtain discrete values corresponding to the number of elements over the thickness. When implementing in the model, the residual stress determined for a specific thickness section was applied to all elements of the corresponding X-Z plane, as the level of the longitudinal residual stresses is almost constant over the plate length and width according to [13] (Fig 5, right).

In [14], the three-dimensional residual stress state of quenched plates was investigated. It was found that the transverse and longitudinal residual stresses have an almost identical magnitude and that the residual stresses in the thickness direction are negligibly small in comparison. Based on this, the longitudinal residual stresses implemented in the model were also adopted for the transverse direction. According to [11], the residual stresses in the thickness direction were neglected.

The three-dimensional residual stress state defined in this way is technically unrealistic due to the large magnitude of the residual stresses. Within the scope of the sensitivity analysis, it was provided with a scaling factor and scaled down in order to be able to investigate the effects of the residual stresses at different levels.

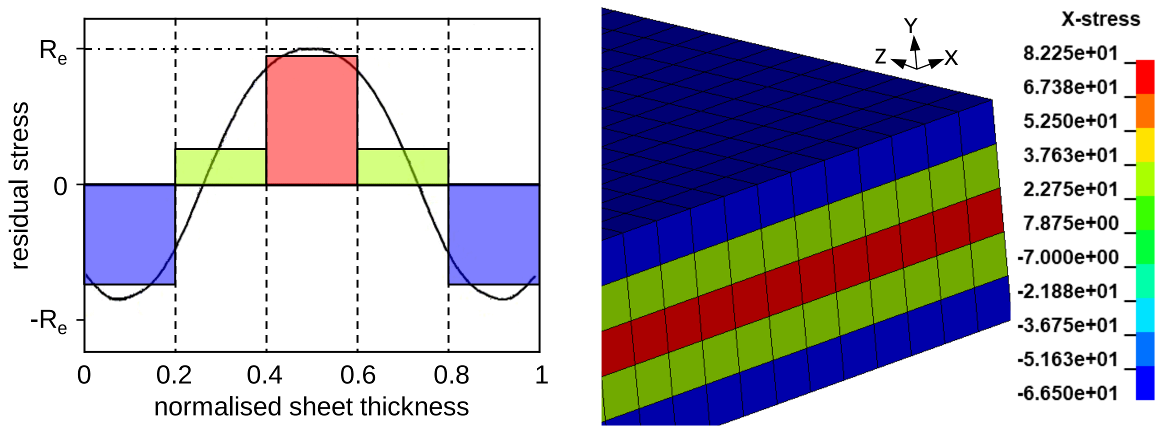

Fig.5: Left: Adaptation of the residual stress curve from [13] for implementation in the model. Right: Section of the FE model of a plate with implemented residual X-stresses (S355, scaling factor of the residual stress state = 0.25).

4 Sensitivity analysis

4.1 Test scope

Within the sensitivity analysis, the influence of various parameters on the forming result of roll bending was investigated. Therefore, a forming process consisting of a bending step with one side roll and a subsequent rolling up to a single complete pass of the plate was simulated. The parameters investigated on the workpiece side were the dimensions of the plate, the material strength and the magnitude of residual stresses, for which a scaling factor was applied to the implemented residual stress state. On the machine side, the infeed angle of the side roll and the stiffness of the support of the bottom roll were investigated. The parameter range for the investigation was chosen close to practice and is listed in Tab. 1. To investigate the influence of the variables efficiently, a D-optimal statistical test plan with quadratic interactions was used, which included 95 simulations.

Influencing parameter	**Parameter range**
Plate length in mm	3750 … 5250
Plate width in mm	1400 … 4000
Plate thickness in mm	50 … 100
Material	S355, S690
Scaling factor of the residual stress state	0 … 1
Feed angle of the side roll in °	16.84 … 49.84
Stiffness of the bottom roll support in MN/mm	2.5 … 7.5

Table 1: Investigated parameter ranges of the considered influencing parameters.

4.2 Evaluation method

To quantify the forming result, the radius of the formed plate was determined for each simulation. To do this, the coordinates of the nodes on the outside of the plate were extracted and imported into Matlab as a point cloud (Fig. 6). Then, the ends of the point cloud were removed in order to limit the evaluation to the continuously formed area. Subsequently, the remaining points of the two middle rows were fitted with circular curves. Finally, the mean value of the radii of these two circular curves was used as a measure for the forming result.

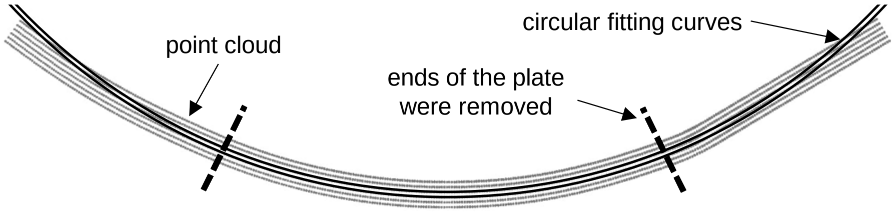

Fig.6: Determination of the radius of a plate after rolling simulation.

5 Results and discussion

The simulation results were analysed in the software Visual XSel using multiple regression with quadratic function approaches. A regression model was created that can predict the forming result for configurations of the influencing variables within the investigated parameter range. The fit of the regression model achieved a coefficient of determination of $R^2 = 0.995$ and thus a very good accuracy. An exemplary model prediction, which illustrates the sensitivity of the forming result to the influencing variables, is shown in Fig. 7. For a certain parameter configuration, which is marked by the red lines, the Figure shows how a change of an influencing variable affects the forming result.

As expected, the feed angle of the side roll has by far the greatest influence on the forming result. Here, the relationship is non-linear, with the slope becoming flatter as the feed angle increases. The influence of the plate thickness is also high. It should be noted that there is a geometric relationship between the plate thickness and the feed angle. With a rising thickness of the plate, the starting angle of the side roll, at which it is in contact with the undeformed plate, becomes smaller. Consequently, an increase in the plate thickness at a constant feed angle means a greater feed distance travelled by the side roll and thus a greater deformation impressed. Furthermore, the influence of the material on the forming result is significant. Here it can be seen that the radius of curvature of the plate increases with increasing strength, so that a smaller deformation is impressed. This is presumably due to the elastic springback that takes place continuously during roll bending. Since the elastic deformation energy stored in the plate increases as the yield point of the material rises, greater springback takes place.

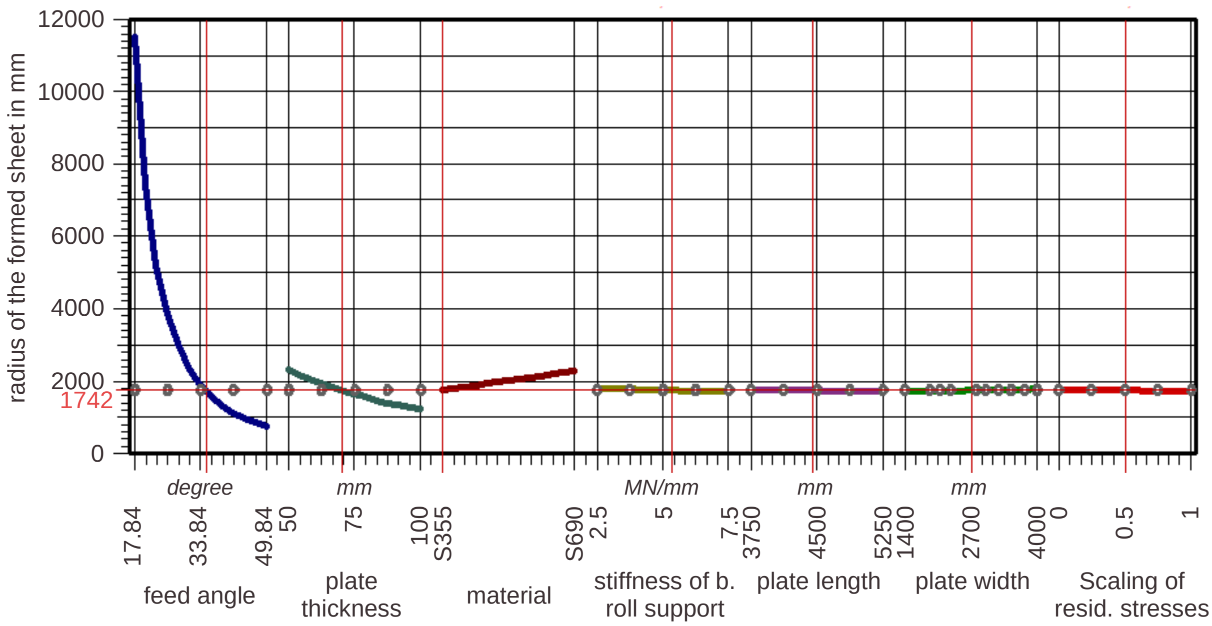

Fig.7: Correlation of the forming result with the influencing variables.

For the other parameters investigated, the influence on the forming result is comparatively insignificant. The small influence of the stiffness of the support of the bottom roll can be interpreted as an indication that the stiffness of a plate bending machine does not have to be known exactly in order to be able to predict the forming result during roll bending reliably. However, it should be emphasised that the supports of the side rolls were assumed to be rigid in the model, which means that the stiffness of the

plate bending machine in the FE model tends to be assumed to be too high. Conclusions on the influence of the stiffness of the plate bending machine are therefore subject to great uncertainty.
From the authors' point of view, the small influence of the plate length and width is surprising. The plate length causes a change in the position of the centre of gravity of the plate behind the roll exit and thus influences the counter-bending moment by its weight. However, in the parameter range considered, this influence is apparently small. The plate width increases the mass of the plate, which leads to an increase in the counter-bending moment caused by the weight. Yet this effect seems to be compensated by the simultaneously increasing bending stiffness of the plate. It should be emphasised that the plate width is of great importance for roll bending in practice, since the bending capacity of a plate bending machine is limited by the bending stiffness of the plate. However, this circumstance is not considered in the model, as the rigid side rolls have been fed in a displacement-controlled manner, which means that the process forces can become infinitely large. This also explains the small influence of the residual stresses. Since the process forces can become infinitely large, the increase or reduction of the forming resistance by residual stresses only plays a subordinate role. The transferability of this determined correlation into practice is therefore dependent on the control of the plate bending machine. With a displacement-controlled infeed of the side rolls, it can be assumed that the influence of residual stresses on the forming result is negligible.

6 Summary

In this work, a computationally efficient three-dimensional FE model for roll bending with a 4-roll plate bending machine was developed in LS-DYNA. The features of the model that should be emphasised are:

1. The model was built parameterised and modular. For this purpose, the process was divided into three sub-steps and an adapted model was created for each. With the help of a Python program, the models can be parameterised on the basis of a predefined forming plan.
2. For the first time for an FE model of roll bending, the residual stresses present in the plate were taken into account. For this, the characteristic residual stress state of thermomechanically rolled plates was determined based on works from the literature and implemented in the model.

With the help of the FE model, a sensitivity analysis was carried out for roll bending. A simple forming sequence consisting of a single bending and subsequent rolling up to a single pass of the plate was simulated and the influence of machine and workpiece parameters on the forming result was investigated. The following results were determined:

1. In addition to the feed angle of the side roll, the plate thickness and the strength of the plate material have a major influence on the forming result.
2. A minor influence resulted from the width and the length of the plate as well as from the residual stresses.
3. In the simulation, the influence of the compliance of the 4-roll plate bending machine respectively the influence of the stiffness of the bottom roll support was small. However, due to the simplified model assumptions, this is subject to a large uncertainty.

7 Acknowledgements

The project *“Qualifizierung eines vereinfachten Ersatzmodells zur Prozesssteuerung beim Walzrunden großer Blechdicken für hohe Umformgrade”* Ref.-No. AiF (20444 BR) was managed and supervised by the Research Association “Forschungsvereinigung für Schiffbau und Meerestechnik e.V. (FSM)”. In the scope of the Program to Promote Industrial Collective Research it was funded by the German Federation of Industrial Research Associations (AiF) with means of the Federal Ministry of Economic Affairs and Energy (BMWi) on the basis of a decision by the German Bundestag.

8 Literature

[1] Gavrilescu, I., Boazu, D. and Stan, F.: "Estimating of Bending Force and Curvature of the Bending Plate in a Three-Roller Bending System Using Finite Element Simulation and Analytical Modeling", Materials, 14(5), 2021, p. 1-16
[2] Zeng, J., Liu, Z. and Champliaud, H.: "FEM dynamic simulation and analysis of the roll-bending process for forming a conical tube", Journal of Materials Processing Technology, 198 (1-3), 2008, p. 330-343

[3] Ktari, A., Antar, Z., Haddar, N. and Elleuch, K.: "Modeling and computation of the three-roller bending process of steel sheets", Journal of Mechanical Science and Technology, 26(1), 2012, p. 123-128
[4] Fu, Z., Tian, X., Chen, W., Hu, B. and Yao, X.: "Analytical modeling and numerical simulation for three-roll bending forming of sheet metal", The International Journal of Advanced Manufacturing Technology, 69(5-8), 2013, p. 1639-1647
[5] Tran, H.Q.: "Asymmetrical Roll Bending Process study: Dynamic finite element modeling and experiments", PhD Thesis, Université du Québec, 2014
[6] Wu, K., Sun, Y., Cao, C., Zhou, C., Liu, Q. and Chang, X.: "On Simulation Analysis of Plate Forming and Deformation Compensation Technology of the side roll for Four-roll Plate Bending Machine", Procedia Engineering, 207, 2017, p. 1617-1622
[7] Wang, Y., Zhu, X., Wang, Q. and Cui, X.: "Research on multi-roll roll forming process of thick plate", The International Journal of Advanced Manufacturing Technology, 102(1-4), 2019, p. 17 26
[8] Zhao, W., Warren Liao, T. and Kompotiatis, L.: "Stress and Springback Analyses of API X70 Pipeline Steel Under 3-Roller Bending via Finite Element Method", Acta Metallurgica Sinica, 30(5), 2017, p. 470-482
[9] Choi, C.W., Koh, H.J. and Lee, S.: "Analysis and prevention of yield strength drop during spiral piping of two high-strength API-X70 steels", Metallurgical and Materials Transactions A, 31(10), 2000, p. 2669-2674
[10] Hua, M., Baines, K. and Cole, I.M.: "Continuous four-roll plate bending: a production process for the manufacture of single seamed tubes of large and medium diameters", International Journal of Machine Tools and Manufacture, 39(6), 1999, p. 905-935
[11] Wagner, M.: "Lineare und nichtlineare FEM - Eine Einführung mit Anwendungen in der Umformsimulation mit LS-DYNA®", Springer Vieweg, 2017
[12] Hockett, J.E. and Sherby, O.D.: "Large strain deformation of polycrystalline metals at low homologous temperatures", Journal of the Mechanics and Physics of Solids, 23(2), 1975, p. 87 98
[13] Prime, M.: "Residual Stresses Measured in Quenched HSLA-100 Steel Plate", 2005
[14] Arbab Chirani, S., Retraint, D. and Lu, J.: "Study of through-thickness residual stress by numerical and experimental techniques", Journal of Strain Analysis for Engineering Design, 33, 1998, p. 449-458