Investigation of the roller straightening process for long products

Untersuchung des Richtprozesses für Langprodukte

Dr.-Ing. **Koos van Putten** and Dr. **Thomas Daube**,
SMS Meer GmbH, Mönchengladbach;

Kurzfassung

In dieser Veröffentlichung werden die ersten Ergebnisse eines neu entwickelten, impliziten Simulationsmodells des Richtprozesses für Langprodukte vorgestellt. Im Modell wurden realistische Randbedingungen implementiert; der Transport des Langproduktes durch die Richtmaschine wird durch eine Drehbewegung der Richtscheiben unter Berücksichtigung der (Coulomb'schen) Reibung abgebildet. Exemplarische Ergebnisse des Richtens eines HE 240A Trägers in einer elf Rollen CRS®-Richtmachine und einer 192 x 150 – 75 kg/m Schiene in einer neun Rollen CRS®-Richtmaschine werden diskutiert. Die Richtkräfte und Antriebsmomente können somit in diesem Modell bestimmt werden. Diese Richtkräfte zeigen eine gute Übereinstimmung mit den gemessenen Kräften. Bei den berechneten Antriebsmomente ist dies nicht der Fall. Als Ursache für diese Abweichung ist wahrscheinlich die Vorgabe starrer Drehzahlsollwerte an den Richtrollen. Weitere Ergebnisgrößen sind die Spannungen im Langprodukt während und nach dem Richtprozess. Die berechneten Spannungen konnten bisher noch nicht anhand von experimentellen Daten validiert werden. Aus der Praxis bekannte Effekte, wie z.B. Steghöhezunahme oder Schienenlängezunahme, wurden im Simulationsmodell ebenfalls beobachtet. Es ist geplant, dass Simulationsmodell in naher Zukunft zu erweitern und zu optimieren.

Abstract

This publication presents the first results of a newly developed implicit simulation model of the straightening process for long products. Realistic kinematic boundary conditions are implemented in the model; the longitudinal movement of the product through the straightening machine is accomplished by the rotational movement of the rollers and the (Coulomb) friction. Exemplary results of the straightening of an HE 240A section in an 11 rollers CRS® and a 192 x 150 – 75 kg/m rail in a 9 rollers CRS® are discussed. Forces and torques on the rollers are calculated. The calculated forces are in the range of experimentally

measured forces, the calculated torques deviate from the measurement. This deviation is probably caused by the prescription of rigid motor speed set points in the simulation. The stresses in the rail during and after straightening are calculated as well, but they have not been validated by experimental measurements yet. Well-known global effects, such as increasing web height or rail length increase occur in the FE simulations as well. The model is still under development and will be further expanded and improved in the near future.

1. Roller straightening of long products

The straightness of a long product (e.g. rail, H-section, I-section) is one of the most important factors for the quality and commercial value, but long products are distorted after hot rolling and the subsequent cooling on a cooling bed. The curvature of the product is mainly caused by the residual stresses which are induced by inhomogeneous cooling, transformation induced plasticity (TRIP), frictional effects and bending. The residual stresses in the feet of railway rails are limited according to international standards. To meet the demands for straightness of long products and to reduce the residual stresses in the product, a straightening step by means of roller straightening is added to the production chain. In roller straightening a long product moves through a series of driven rollers, which are located alternately below and above the long product. While the long product is passing through the rollers in the longitudinal direction, it is bent up and down. The plastic deformation caused by a combination of bending, shear and roll contact stresses during straightening homogenises the residual stresses and decreases the initial distortion. This operation is very important because it is the final deformation process of the production chain, which determines the residual stress pattern. Although the principle of up and down bending itself is quite simple, obtaining a straight rail and reducing residual stresses are difficult tasks because the straightness also depends on the distribution of the residual stresses [1].

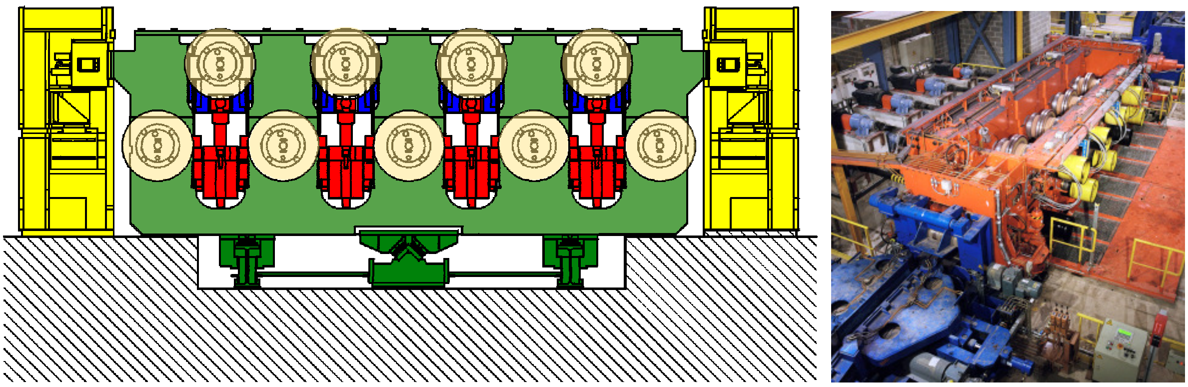


Fig 1: Nine roller Compact Roller Straightener (CRS®)

The state-of-the-art straightening technology developed by SMS Meer is the Compact Roller Straightener (CRS®) with hydraulic roller adjustment system designed for straightening sections, rails, channels, sheet piles and special sections. The design of a CRS® is tailor-made, related to customer requirements and uses standard parts for easy maintenance. The main features of the CRS® are:

1. Hydraulic vertical and axial roller adjustment
2. Double mounting of straightening shafts (symmetrical straightening force introduction)
3. Improved straightness by minimised internal stress
4. Single drive system of straightening shafts

With the CRS®, an off-line roller straightener setup model for calculation of vertical adjustment values has been developed. This is a semi-empirical calculation model which calculates the roller adjustment, bending line, curvature, straightening forces and bending moment. The short calculation times of the roller straightener setup model (approx. 60-80 s) enable the prescription and optimisation of the roller adjustments during the commissioning of new products.

However, for analysing the internal stress during and after the straightening process (residual stress) and for determining unstraightened ends, a finite element approach is necessary. Additionally, the straightening forces and motor torques can be calculated on the basis of first principles this way. These are important magnitudes for further development of roller straighteners and the optimisation of the straightening process.

2. State-of-the-art in the simulation of straightening processes for long products

It is difficult to set-up a straightforward FE model with reasonably short calculating times for two main reasons. First, it is difficult to obtain stable contact conditions. In FE simulation models of straightening processes, the contact area between long product and roller is generally relatively small. Additionally, a high number of contact releases and contact captures per increment will occur throughout the simulation. Second, the length of the long product in the straightener is usually more than 6 m, depending on the pitch. This results in a long workpiece in the simulation model with correspondingly high numbers of nodes and elements.

To avoid this, either several simplifications are made or the simulation is performed with the aid of a dynamic explicit FE code. Simplifications often made are among others, the usage of beam elements, neglect of the movement of the product through the roller straightener, assumption of frictionless contact combined with non-rotating rollers. Accelerated explicit analyses (by mass scaling or time scaling) usually require less computation time. Furthermore explicit analyses are less sensitive to non-linearities such as (unstable) contact and non-linear material behaviour. However, in explicit analyses the mechanical equilibrium is not checked after each time step. This can - especially in (quasi) static problems - lead to deviations of the calculated magnitudes.

Schleinzer and Fischer [2] set up a model which not only deals with bending moments and forces, but also with the longitudinal movement of the rail through the straightening machine. In order to achieve reasonable computing times with a sufficiently fine mesh, the straightening simulation was split into two runs. In a first run, the global model, the movement and the bending line of the rail were calculated with the aid of Abaqus Explicit. In a second run with the aid of Abaqus Standard, the submodel, a short part of the rail is moved through the straightener, again including all contacts with the rollers. The history for the roller operation of the global model, the adjustment of the deflection and the subsequent rotation, are the boundary conditions for the submodel. In the submodel the Chaboche multiple component nonlinear kinematic hardening material model accounted for the plastic material behaviour. The benefit of this approach is that it dispenses with major simplifications, and that an implicit code is used to calculate the residual stresses. However, the computation time remains long (10 days), two different models have to be set up and the model is not fully implicit.

Hayakawa et al. [3] simulated the straightening of an H-section profile in a 9 roller straightener with the aid of Abaqus Explicit. The H-section was fed into the straightener by the frictional force of the rotated bottom rolls. The upper rolls were all fixed. A friction coefficient was defined between the H-section and the driven bottom rolls, the contact between the H-section profile and the upper rolls was assumed to be frictionless. To account for the cyclic tension-compression loading of the beam, Armstrong-Frederic combined hardening law was implemented. The simulation was evaluated by means of the beam deflection, stress and accumulated equivalent plastic strain distribution and the web height. In order to consider the effects of the elastic deformation of the roller straightener frame, the model was modified in a second phase. The upper rolls were supported by spring elements, whereas the position of the bottom rolls remained fixed. The simulation can analyse the change of the cross section and the (accumulated) deformation at the transition between the flange and the web. The stiffness of the machine frame (the springs in the 2nd model) has a significant influence on the longitudinal deflection. However, the model was neither verified with experimental results nor quantitatively evaluated. The influence of the assumption of the frictionless and non-rotating upper rolls is not evaluated or discussed.

3. Objective and scope

Based on the state-of-the-art in the FE simulation of straightening processes for long products, SMS Meer aims to develop a three dimensional FE model of roller straightening. This model should represent the process as realistically as possible and therefore abstain from simplifying assumptions. It is intended that the FE model can be used to;

1. assist with the lay-out of straightening machines (calculation of roller force and roller driving torque);
2. optimise process parameters, roller adjustment in particular, evaluated by means of the calculated straightness, unstraightened end lengths, cross sectional geometry at given process parameters;
3. calculate residual stresses after straightening.

This publication presents the first results of the simulation of two different straightening processes. One model simulates the straightening of an HE 240A section in an eleven roller CRS®. The other model simulates the straightening of a 192 x 150 – 75 kg/m rail in a nine roller CRS®. Due to lack of experimental data, only the HE 240A straightening could compared with practical measurements.

3. FE model set-up

The finite element simulation modelling was performed with the aid of Simufact Forming 9.1. The models are three dimensional but the YZ-symmetry plane is used, so only half of the H-section and the rail are modelled. For both, the H-section straightening as well as the rail straightening, isothermal process conditions are assumed, the analyses are mechanical. In both models the rollers are modelled as non-deformable rigid bodies. The rollers all have a constant circumferential speed of 2 m/s and a diameter of approx. 1000 mm. The rollers are placed in their adjusted position. The roller adjustments of both simulated process are experimental and confidential. Coulomb friction is assumed. The friction coefficient is set to 0.15. At the current project stage, the material model is still simplified. The cyclic tension-compression loading is not yet taken into account. Elastic-plastic material behaviour is used;

the yield stress of the material is set to a constant value of 320 N/mm² and 760 N/mm² for the H-section and rail respectively. For the sake of simplicity, the unstraightened long products in the FE models are straight, curvature due to primary processes are not taken in account here, and free of any residual stresses. The long products are meshed with fully integrated hexahedral elements. The H-section is meshed with 60750 elements and the rail with 58400 elements. The cross sectional meshes of both models are depicted in Fig 2.

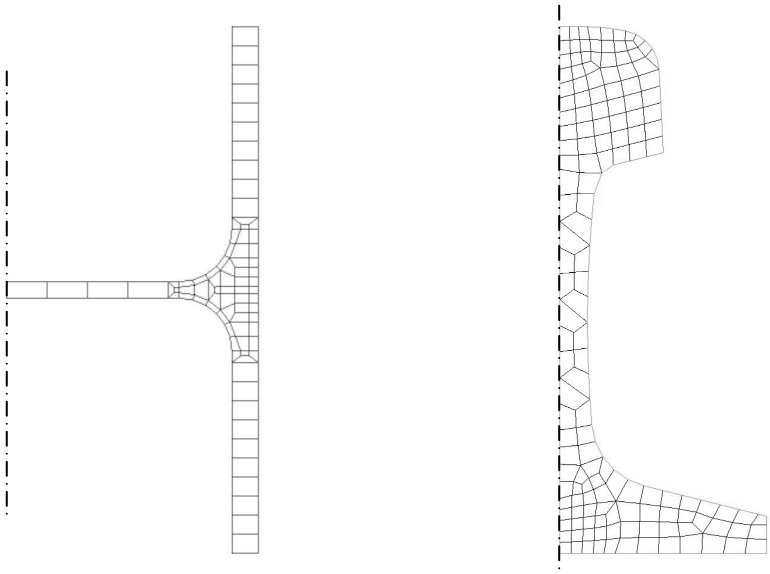


Fig. 2: Cross sectional meshes applied in H-section and rail straightening

The dead load of the still unstraightened part of the long product at the entrance forms a natural boundary condition and prevents the product from tilting up. In the simulation model the length of the long products is limited to reduce the number of elements and gravity is not implemented to reduce the calculation time. To avoid excessive upwards movement of the profile's end at the entrance to the CRS®, a guide is implemented in the model. The long product runs through this guide, the guide restrains the upward (vertical) movement of the product. Fig. 3 shows the simulation model of the H-section straightening in the initial state. Fig. 4 presents the model of the rail straightening in a state where the guide as well as all the rollers are in contact with the rail.

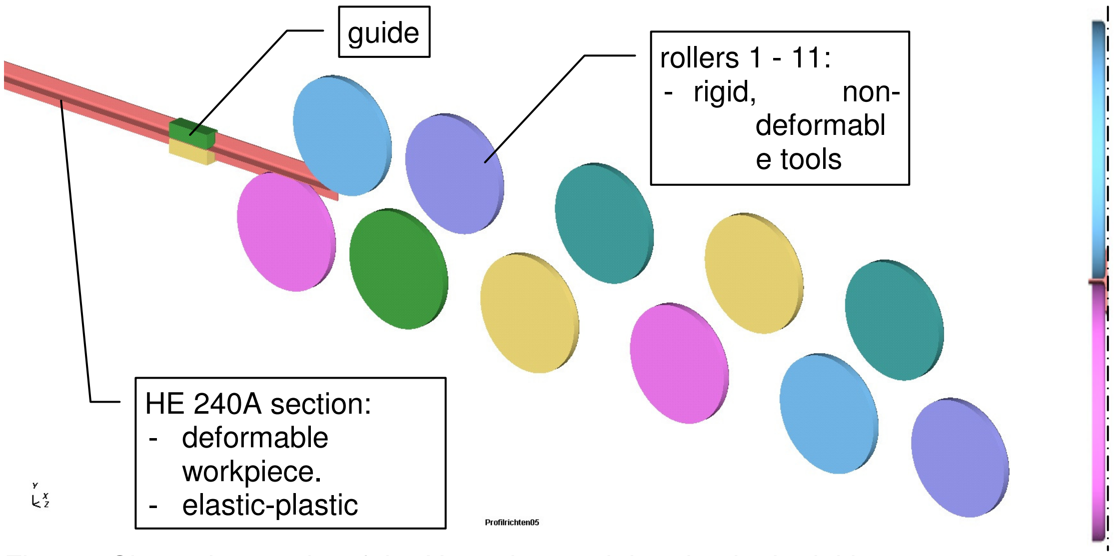


Fig. 3: Simulation model of the H-section straightening in the initial state.

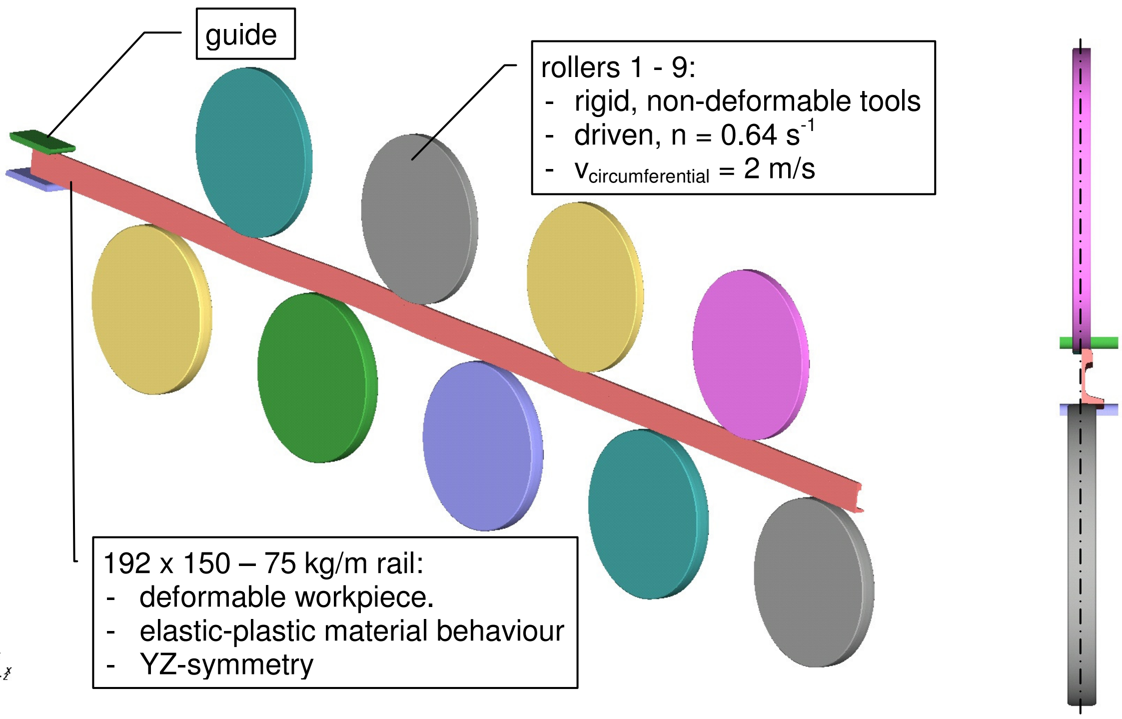


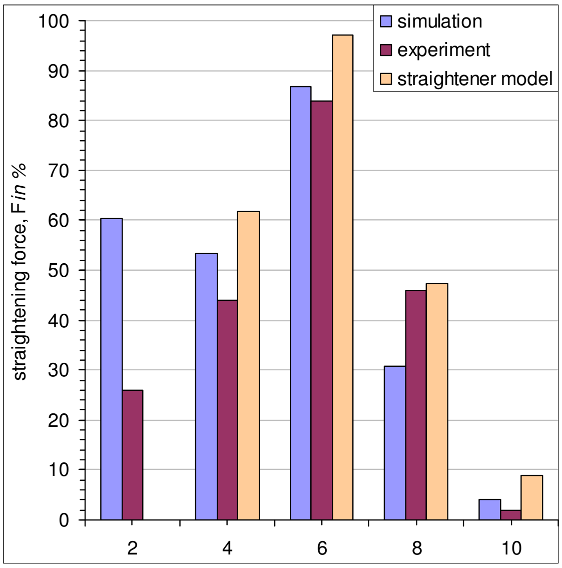
Fig. 4: Simulation model of the rail straightening in a state where the guide as well as all the rollers are in contact with the rail.

4. Results

Because experimental data are available for the H-section straightening only, emphasis in this section lies on the discussion of these simulation results. The FE results of the rail straightening are presented more briefly.

4.1 Straightening force and driving torque

The straightening force in the experiment was measured at the adjustable upper rollers. The measured force is compared with the force calculated by the FE simulation and by the semi-empirical straightner model (Fig. 5). The force at the 2^{nd} roller calculated by the FE simulation is substantial higher than the measured force. This discrepancy is probably caused by the implementation of the entry guide in the simulation model. Restraining all vertical (upward) displacements is probably not in accordance with the reality. Although the dead load forms a natural boundary condition in the real process, a slight tilting upwards of the profile will still be possible due to elastic bending of the H-section. The other calculated forces are in quite good agreement with the measured ones, although some improvement in accuracy is required. The trend however, is in good agreement.



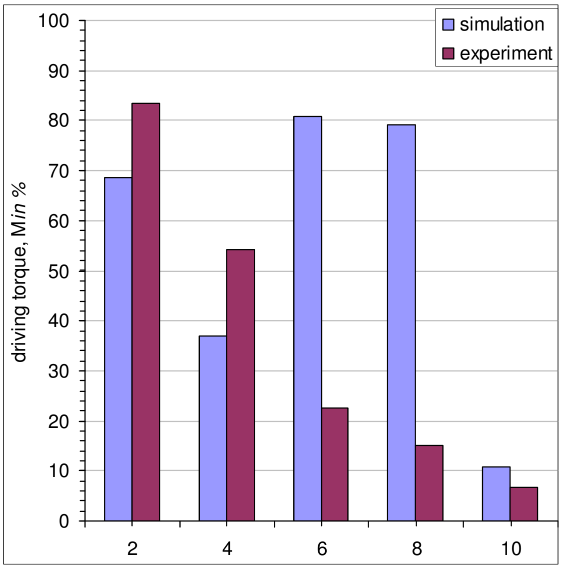


Fig 5: Comparison of the measured and calculated straightening forces (left) and driving torques (right) of the HE 240A section straightening.

There exists a clear discrepancy between the measured and the calculated driving torque. This discrepancy is ascribed to the influence of the rotational speed control active in the real process but not implemented in the simulation model. To improve the accuracy of the simulation model, the effect of the rotational speed control must be accounted for in the model.

4.2 Product geometry

From practice, it is known that the flange of an H-section flaps towards the roller during straightening. This effect is observed in the simulation as well. Fig. 6 exemplarily shows the cross sectional geometry of the H-section at four different rollers. The flange moves towards the upper rollers 4 and 6 and moves towards the bottom rollers 5 and 7. The movement of the flange is restricted by the rollers, the maximum displacement is reached when the tip of the flange touches the roller face.

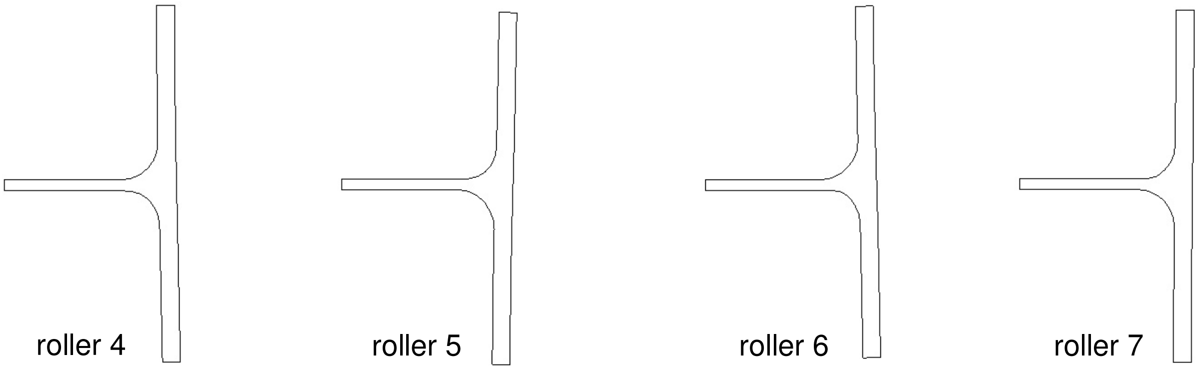


Fig. 6: Calculated cross sectional geometries in HE 240A section straightening at different rollers.

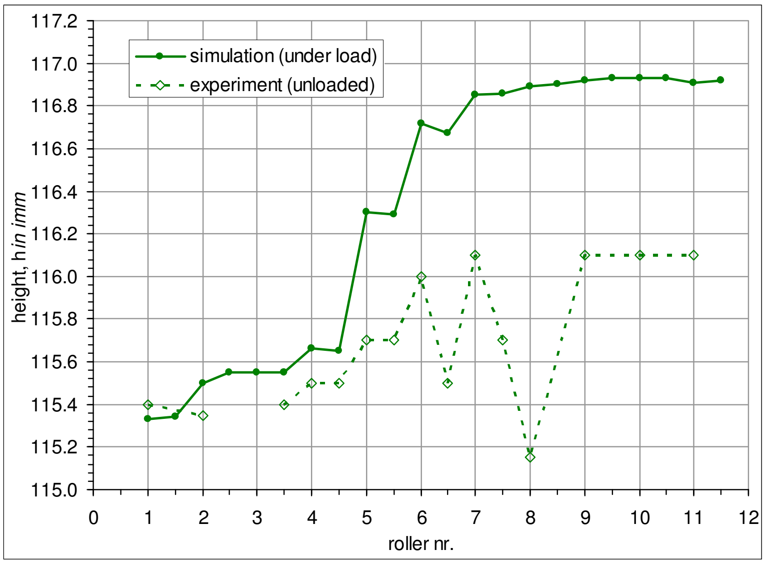


Fig 7: Comparison of the measured and calculated web height during HE 240A section straightening.

The web height of the H-section increases during straightening. This is also a well-known phenomenon in every-day practice. In the experiments, the web height was measured on a straightening stack after unloading the profile. The web height in the simulation has been obtained from the loaded H-section. A comparison of the calculated and measured web height is depicted in Fig. 7. Due to the different conditions under which the web height has been determined (unloaded v.s. loaded) there is no quantitative agreement between the simulation and the experiment. Nevertheless, the trend – increasing web height – can be observed in both results.

In rail straightening it is well known that the rail length decreases during the straightening [4]. This effect also occurs in the simulation of the rail straightening. In the simulation model the length of the rail decreases by approx. 8 ‰ after straightening in the 9 roller CRS®.

4.3 Equivalent strain and residual stress

The calculated distributions of the equivalent strain, the equivalent Von Mises stress and the longitudinal mean normal stress after straightening the HE 240A section are shown in Fig. 8. Of course these variables can be analysed during straightening as well, but as discussed in the introduction the stresses remaining in the product after straightening are of major importance.

A stress concentration is located in the root area at the web end (Fig. 8). This is caused by the flapping of the flange during straightening. Here the material thickness is less than in the root area and this location functions as a plastic hinge for the flapping movement. The flapping accumulates strain and stresses in the plastic hinge. Additionally, local web necking in the plastic hinge occurs. The FE simulation calculates a decrease of the web thickness in the plastic hinge of approx. 6 %. It can be concluded that the area of the plastic hinge is the most critical area concerning residual stresses.
Although the measurement of residual stresses in H-sections and rails is possible [1, 2, 4], this has not been carried out within this project yet. The calculated residual stresses have not been validated, this is planned for a later project stage.

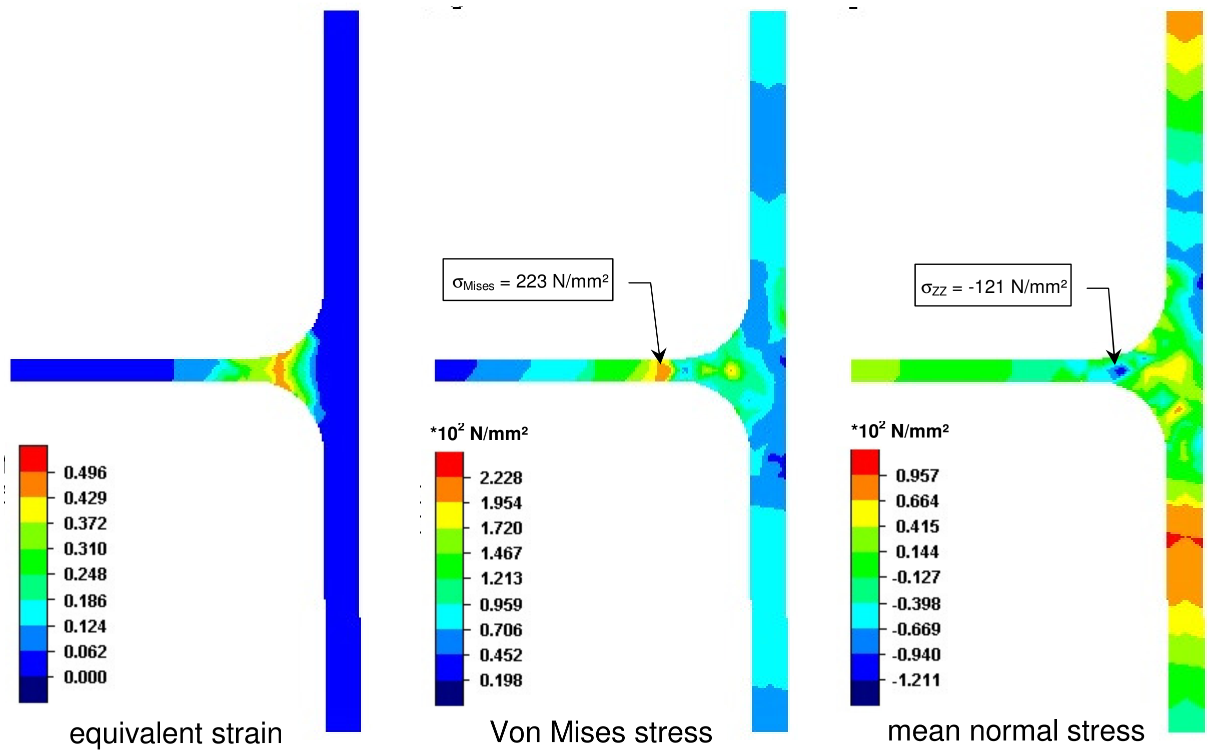


Fig. 8: Distributions of the equivalent strain, the equivalent Von Mises stress and the longitudinal mean normal stress after HE 240A section straightening

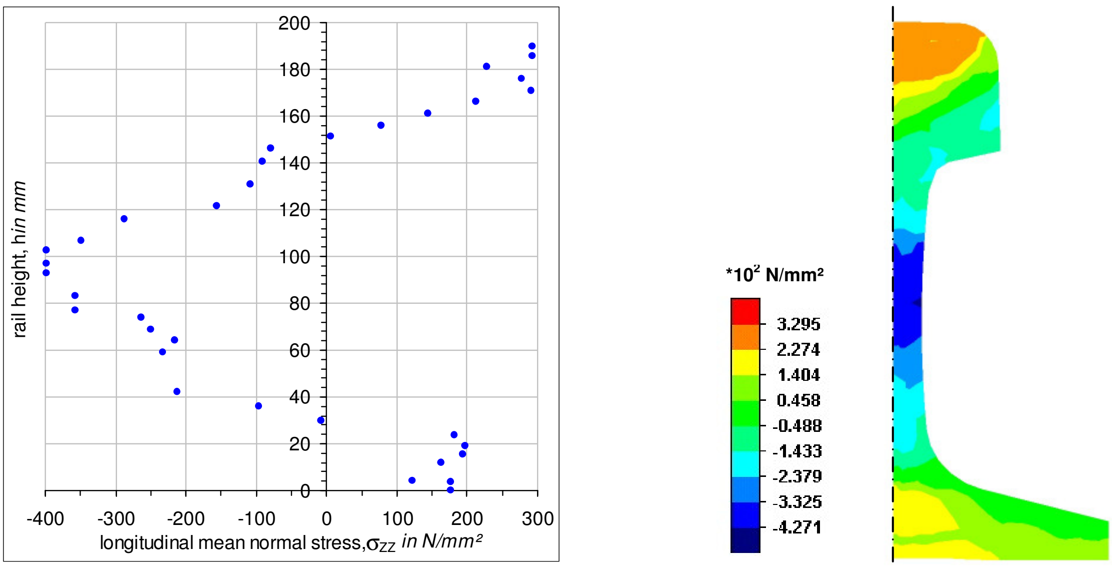


Fig. 9: Longitudinal mean normal stress distribution along the symmetry line (left) and the longitudinal mean normal stress distribution (right) after 192 x 150 – 75 kg/m rail straightening.

The calculated longitudinal mean normal stress after straightening in the FE models is representative for the residual stress in a long product. The calculated stress distribution after rail straightening (residual stress) as well as the calculated residual stress along the symmetry line (Fig. 9) are qualitatively in agreement with experimental and numerical results presented in various literature references [1, 4].

6. Conclusions and outlook

Three-dimensional finite element models of H-section and rail straightening accounting for the 3-dimensional state of stress occurring during and after straightening were set-up. The models refrain from simplifying assumptions in order to represent the process as realistically as possible. The simulations are implicit, but account for the non-linear material behaviour as well as the contact between long product and rollers.

Forces and torques on the rollers can be calculated. The calculated forces are in the range of experimentally measured forces. The calculated torques however, are not in agreement with the measured ones. An explanation for this deviation might be the rotation speed control in the machine which is not implemented in the simulation. The stresses in the HE 240A section and the 192 x 150 – 75 kg/m rail during and after straightening are calculated as well, but they have not been validated by experimental measurements yet. However, the calculated residual stresses after rail straightening are qualitatively in agreement with experimental and numerical results presented in various literature references.

Concerning some global effects, such as increasing web height or rail length reduction, well known from practice, a qualitative agreement between real process and FE model exists. These effects occur in the FE-simulations as well.

To further improve the accuracy of the force calculation, the guide at the entrance to the CRS® will be made less rigid so that it better represents the influence of the dead load of the unstraightened part of the product. A better agreement between the calculated and measured driving torques can probably be achieved by the implementation of the rotation speed control in the FE model. Furthermore, the material model will be improved so that it accounts for the cyclic tension-compression loading occurring during the straightening process.

7. References

[1] Fischer,F.D.; Schleinzer, G.: Residual stress formation and distrortion of rail steel. Handbook of residual stress and deformation of steel. Eds.: Totten, G.; Howes, M; Inoue, T.; 2002, 424 – 436

[2] Fischer,F.D.; Schleinzer, G.: Residual stress formation during the roller straightening of railway rails. Int. J. Mech. Sc. 43, 2001, 2281 – 2295

[3] Hayakawa, K.; Nakamura, T.; Tanaka, S.: Finite element analysis on straightening process of cross-sections by roller leveler. Proc. 12^{th} Int. Conf. Metal Forming, 2008, Krakow

[4] Weiser, J.: Analyse der Eigenspannungsentstehung beim Rollenrichten von Schienen. Otto von Güricke Universität PhD-thesis. Magdeburg 1997