FE-BASED SENSITIVITY ANALYSIS OF FLATNESS IN HOT HEAVY PLATE LEVELING*

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Abstract

Leveling is a standard process in the rolling mill to eliminate flatness deviations. The process layout is based on models and the leveling result depends on the accuracy of the material parameters in these models. Even small deviations from the correct assumptions can have a major effect on the final flatness. Thus, after leveling the products may look optically flat, but subsequent to a final cutting process springback occurs due to residual stresses. The objective of this work is to analyze the influence of material parameters and gravity on the flatness after leveling. To evaluate the sensitivity of the process, an FE parameter study is exerted that reveals the influence of fluctuations in material properties in the case that the leveling setup is fixed. Gravity is neglected to not conceal flatness deviations. Examples of this study are rerun in a further step under consideration of gravity to also analyze its influence on the resulting flatness and residual stresses. Finally, to analyze the consequence of the residual stresses, all information of the plate from the previous step are transferred while gravity is suppressed to prompt springback. This study revealed that slight deviations of the material properties can lead to uneven plates in simulations where gravity is not considered. If gravity is taken into account, the unevenness is concealed and the plate seems flat. A springback simulation of the same plate shows that strong residual stresses are still present and would lead to unevenness if e.g. the plate were cut.

Keywords: Hot heavy plate leveling; Finite Element Methods; Springback.

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1 INTRODUCTION

In the production of heavy plates, besides mechanical properties, flatness is a crucial factor to meet the costumer's requirements. Deviations of the flatness may arise as a consequence of improper process conditions in manufacturing steps such as hot rolling or cooling. To achieve the required flatness, leveling machines have to be used. During the leveling process, the plate undergoes alternating bending operations whereby the material is deformed elastic-plastically [1].

If a leveler is ideally adjusted, the plate leaves the machine perfectly flat and without any curvature. In contrast, the consequence of a non-ideal setup is demonstrated in the following Figure 1.

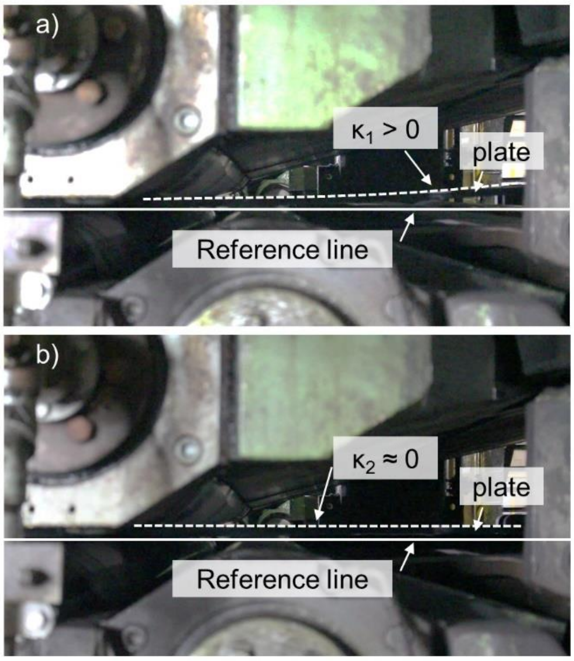

Figure 1. Resulting curvature in the case of a non-ideal roll-setup at the beginning a) and in half of the process b) on an industrial leveler.

At the beginning of the process (Figure 1a), a strong and positive curvature $\kappa_1 > 0\ m^{-1}$ of the plate is optically visible. As the process progresses, the curvature at the exit decreases continuously until an optically flat plate is recognizable $\kappa_2 \approx 0\ m^{-1}$ (Figure 1b). It should be added that after leveling, ski defects were visible both on the head and at the tail of the plate. In the center area, the flatness was almost perfect with a curvature close to zero. According to this, a visually good flatness is achieved in a large part of the plate despite non-ideal roll-setup.

Even if plates are optically flat after leveling, in unfavorable cases flatness deviations may arise after a subsequent cutting operation [2,3]. This is due to residual stresses in the material induced e.g. by using inaccurate material parameters to design the leveler setup. Due to gravity, the plate first remains flat after leveling but as a result of changing boundary conditions during cutting, the stresses are released and the plate springs back. This springback behavior is hard to predict.

Nowadays, finite element (FE) models are utilized to design and optimize the leveling process: Silvestre et al. [4], Negami et al. [5] as well as Lee et al. [6] used FE-leveler models in order to investigate the leveling process. It has been demonstrated that FEM is an efficient tool for investigating both flatness and residual stress aspects. Grüber et al. [7] used an FE-leveler model to determine the roll positions of the leveler which lead to a flat sheet using a controlled approach. Accordingly, many FE-based models to investigate the leveling process exist. Such models can also reveal the influence of material properties on the resulting flatness [8]. In addition, in simulation gravity can easily be considered or neglected to evaluate its effect on flatness and the formation of residual stresses.

Within this work both aspects, the influence of material parameters and gravity on the flatness after leveling are analyzed using FEM. The analysis is divided into three successive steps:
Firstly, to obtain a basic process understanding, an FE parameter study is exerted that reveals the influence of

fluctuations in material properties on the resulting flatness in the case that the leveling setup is fixed. This study shows how sensitive the process is with regards to material parameters and if small fluctuations in material parameters can deteriorate the leveling results. Gravity is neglected to not conceal any flatness deviations.
Secondly, a case where inaccurate material parameters led to an uneven plate after leveling is selected from the previous study. The simulation is rerun under consideration of gravity to analyze its influence on the resulting flatness. Residual stresses may be present in the plate leveled in this way.
Thirdly, to analyze the consequence of these residual stresses a springback investigation is carried out. Here, the residual stresses of the leveled plate from the previous step are transferred while gravity is suppressed to prompt springback. In consequence the stresses may redistribute and cause flatness deviations. Softening mechanisms during hot leveling at elevated temperature are not taken into account in these simulations. In order to assess their influence on residual stresses and thus springback, stress relaxation tests are carried out. Subsequently, separate springback simulations with reduced residual stresses were carried out to evaluate the influence of softening on springback.

2 MATERIAL AND METHODS

Following the material and common model assumptions as well as the different types of FE models and experimental basics of this work are introduced. All simulations in this work were carried out using the software Abaqus CAE 6.14.

2.1 Material and common model assumptions

For the investigations presented in this paper, a conventional structural steel S355 at a temperature of 800 °C is considered. In the starting condition, the initial yield stress is assumed as 100 MPa and the Young's modulus is 140 GPa. The flow curve of the material was determined using a hot tensile test under quasi static conditions. A strain rate dependency of the material is not taken into account. Within the model, isotropic hardening according to the measured data from the experimental hot tensile test is used. It is assumed that the influence of the temperature loss during the leveling pass is negligible and the temperature inside the plate is constant. Thus an isothermal FE-simulation is used and no further thermal parameters are required. The dimensions of the plate are 4500 mm in length and 10 mm in thickness. The plates in the simulations are assumed to be perfectly flat initially, so that results are independent of flatness defects of the incoming plate.

2.2 FE-Model for leveling

The FE leveling model was designed according to the dimensions and kinematic boundary conditions of a real 9-roll heavy plate hot leveler (Figure 2).

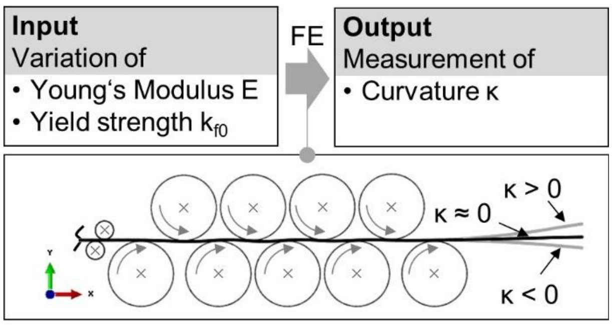

Figure 2. FE leveling model and schematic procedure.

All leveling rolls are modeled as rigid bodies. The lower rolls are located on a horizontal axis. Only rotation of the rolls is possible. The upper rolls allow a movement in the y-direction in addition to the rotation. The upper rolls are aligned to each other in such a way that for the given initial set of material parameters (Young's modulus of 140 GPa and initial yield stress

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of 100 MPa), a flat plate is achieved while the maximum plastic ratio is 80 %. The positions to meet these requirements were determined by a separate simulation using a controlled leveling model with subroutines [9]. The definition of flatness is based on the standard (DIN EN 10029) [10]: If a 2 meter ruler is placed anywhere on the surface of the plate, the maximum distance must not exceed 10 mm in this specific case. Assuming a circular curvature and a maximum distance at half the measuring length, a maximum curvature κ of 0.02 m^{-1} can be derived. Gravity is not considered within the model. This excludes the influence of gravity on the resulting curvature. Since the absence of gravity leads to oscillations of the incoming plate, there are two additional support rolls at the entrance of the leveling model.
Within the scope of the investigations, the material-specific parameters Young's modulus and initial yield stress are separately varied in a wide range around the initially boundary conditions. The roll positions are not adapted to the varied input variables. As a result, the roll positions for the new input variables are no longer ideal and the plate leaves the leveler curved. The resulting curvature after leveling is then used to evaluate the sensitivity of the process with regards to the material parameters.

2.3 FE-Model extension for gravity

To investigate the influence of gravity, the FE model described in chapter 2.2 was extended by a roller table and gravity acceleration of g = 9.81 ms^{-2} (Figure 3). All boundary conditions are the same as in the previous model.

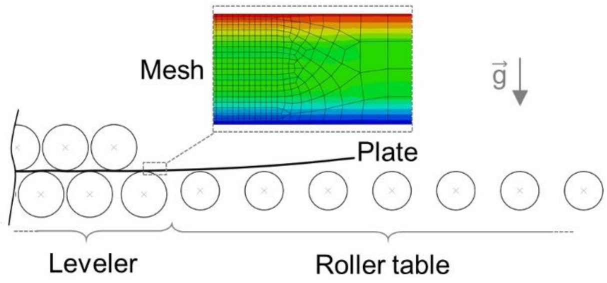

Figure 3. FE model for the investigation of the influence of gravity on the leveling results.

In order to measure residual stresses reasonably and with high resolution across the plates thickness, the mesh was refined locally.

2.4 FE-Model for Springback

In order to assess the geometry change due to stress relieve after leveling, e.g. due to cutting, a springback simulation is necessary. For this purpose, a plate with all its properties is imported into a new implicit simulation without tools. The springback simulation does not take gravity into account. Static simulations, including the springback analysis used here, require that rigid body movements are excluded. These constraints are necessary because dynamic effects cannot be included in a static analysis. Without constraints, a low load would cause the entire workpiece to move rigidly without creating stress [11]. For this reason, a single node was fixed in the model, i.e. all degrees of translation (ux=uy=uz=0) and rotation (urx=ury=urz=0) freedom were suppressed (Figure 4).

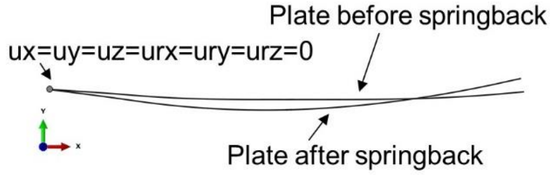

Figure 4. Dependence of the resulting curvature on Young's modulus and initial yield stress.

2.5 Scenarios to evaluate the influence of gravity and material parameter deviations

The influence of gravity and the deviation of material parameters is evaluated on the basis of three different scenarios. As mentioned, the roll-setup in the initial situation for a Young's modulus of 140 GPa and initial yield stress of 100 MPa leads to a flat plate after levelling. The Young's modulus is used in this case to purposely deviate from this situation and cause a curvature due to leveling. The three scenarios are summarized in Table 1.

Table 1. Overview of the examined scenarios

	E-Modul	roll-setup	gravity
Scenario 1	140 GPa	ideal	disabled
Scenario 2	160 GPa	non-ideal	disabled
Scenario 3	160GPa	non-ideal	enabled

Scenario 1 corresponds to a reference study which results in a flat plate with disabled gravity. In scenario 2, gravity is still disabled but the Young's modulus is increased to 160 GPa. Consequently, the curvature after leveling will change. In scenario 3, the Young's modulus is also set to 160 GPa, but in this case gravity is enabled. After leveling, all resulting curvatures are measured. The curvature is measured in the center area of the plate to exclude of ski defects (curvatures only locally at the beginning and end of the plate).

2.6 Stress relaxation test

A stress relaxation test for the steel S335 was carried out at 800°C to evaluate the reduction of stresses due to high temperatures. For that a cylindrical samples with a dimension of 10 mm x 5 mm was used. The tests were performed as follows: After a heating phase and subsequent cooling to a temperature of 800 °C, the sample is compressed with a strain of 5 % using two punches. After compression, the punch positions are fixed. During this time, stress relaxation occurs as a result of softening, which is recorded as a change in force and thus stress over time.

3 RESULTS AND DISCUSSION

In the following, it will be first evaluated to what extent deviations in the assumption of the material parameters lead to a curvature after leveling. Afterwards, the influence of gravity on the geometry and residual stresses is evaluated. Finally, springback with and without the consideration of softening effects of the material under hot conditions is investigated.

3.1 Influence of the material parameters on the curvature after leveling

Figure 6 shows the results regarding the influence of the material parameters on the curvature after leveling with respect to the Young's modulus E and the initial yield strength k_{f0}.

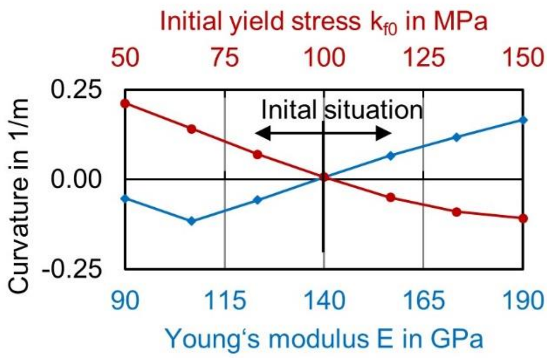

Figure 6. Dependence of the resulting curvature on Young's modulus and initial yield stress.

The initial situation is represented by using the reference values (E = 140 GPa and k_{f0} = 100 MPa) where a flat plate with a curvature close to zero is achieved. Based on this situation, Young's modulus E and initial yield stress k_{f0} were varied separately without changing the roll positions.

A change in the material parameters has a visible effect on the resulting curvature. The reason for this is that the variation of Young's Modulus E and initial yield strain k_{f0} values according to Equation (1)

$$T = 1 - \frac{\frac{k_{f0}}{E}}{\varepsilon_{max}} \quad (1)$$

results in a change of the plastic ratio T (ε_{max} is the maximum strain of the plate within the leveler). There is an ideal roll-setup of roller positions for each given set of material parameters and plastic ratio. As a result of the change in the material parameters and thus in the plastic ratio, the applied roll-setup is no longer ideal.

In addition, Figure 6 shows that if the Young's modulus is assumed to be too high, the resulting curvature tends towards positive curvatures $\kappa > 0\ m^{-1}$. This can be explained by the fact that an increase in the Young's modulus while keeping the initial yield strength constant leads to a reduction in the required strain at which a material changes from elastic to plastic behavior. As a result, the plastic ratio is higher, resulting in higher bending.

In contrast the influence of the initial yield strength on the resulting curvature show an almost inverse behavior compared to the Young's modulus. This seems plausible as the explanation given previously also holds in this case.

Following, selected examples will be used to investigate how gravity influences these results.

3.2 Influence of gravity on the leveling results

The results of the three scenarios (cf. Table 1) regarding the resulting curvature, geometries and stresses over the thickness are summarized in Figure 7.

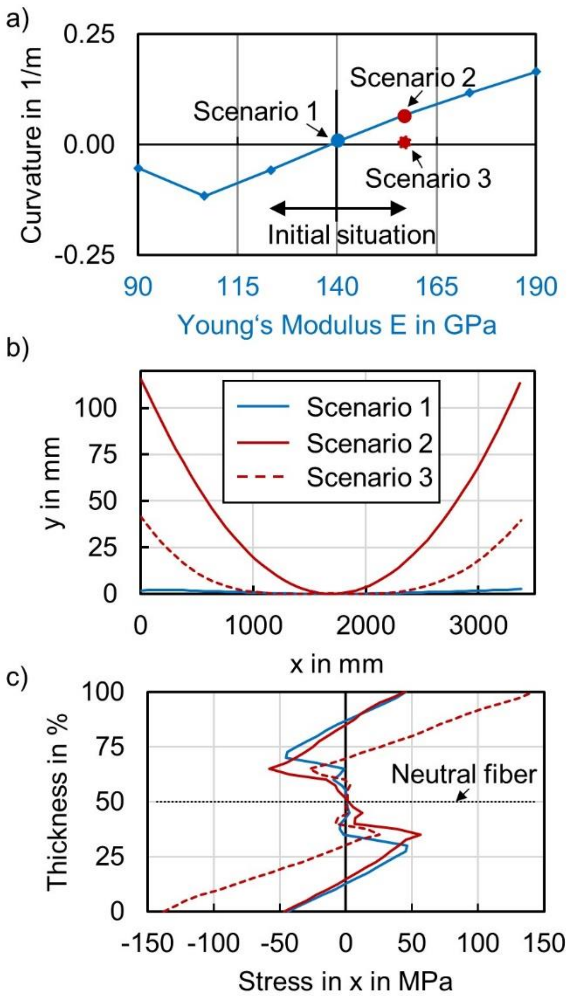

Figure 7. Curvature a), geometry b) and residual stresses c) for the scenarios 1-3.

As expected, scenario 1 without considering gravity and ideal roll-setup for the initial situation results in a curvature close to zero (Figure 7a) and accordingly a geometrically flat plate (Figure 7b). With regard to the residual stresses (Figure 7c), a zigzag characteristic can be seen over the thickness. This characteristic is typical for the stress curve after leveling and results from the alternating cyclic bending in the process. This state corresponds to an equilibrium of the moments which is indicated by the fact that the area fractions in tension and compression above and below the neutral fiber are about the same size.

Scenario 2 with an increased Young's modulus shows a severe curvature after leveling (Figure 7a, b). The characteristic of the stresses is comparable to scenario 1

(Figure 7c) while the maximum absolute values of the stresses are slightly higher. This can be explained by the Young's modulus increase compared to scenario 1 with otherwise unchanged roll positions. The higher the modulus of elasticity, the higher the plastic ratio (cf. Equation (1)). A higher plastic ratio results in higher strain hardening of the material, which explains the higher maximum stress values. Scenario 2 also is in equilibrium with regards to bending moments over thickness.

The simulation of scenario 3 differs from scenario 2 only in that gravity is considered. When comparing the resulting curvature, it is noticeable that the plate in scenario 3 is flat in the center area and there are ski defects at the ends of the plate. The flat part seems to be small in this case, but this is only due to the short length of the simulated plate. In reality, the length of plates is up to 40 meters, so that the flat part is predominant.

Regarding the stresses in scenario 3, it is apparent that the stresses over the thickness are not in equilibrium. In the upper half, tensile stresses dominate while compressive stresses prevail in the lower half. This is reasonable, since without gravity there would be a constant curvature, as in scenario 2. By taking gravity into account, however, the plate is forced towards the roller table so that the fibers above the neutral fiber are stretched, resulting in tensile stresses. Below the neutral fiber however, the fibers are compressed, resulting in compressive stresses. Under such conditions, springback can be expected when the gravity load is relieved which is evaluated in the following section.

3.3 Springback simulation

In order to assess the geometry change due to springback, a separate simulation was carried out for scenario 3. The results regarding the geometry and stresses are shown in Figure 7. To compare the results, the geometry and the stresses of scenario 2 are also given.

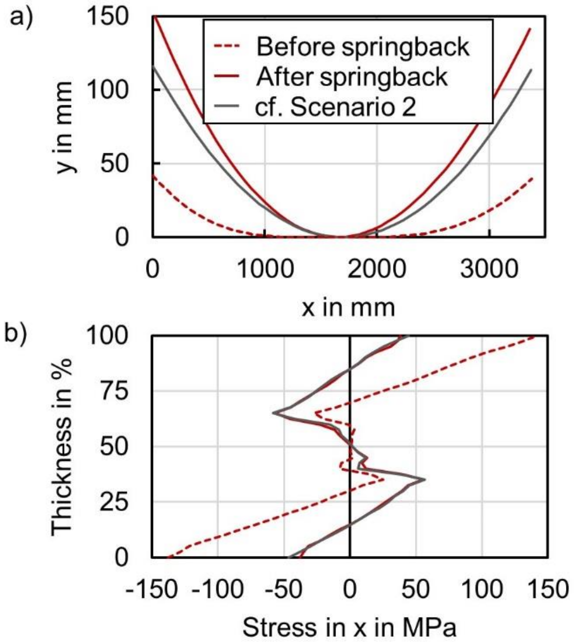

Figure 7. Plate geometry a) and residual stresses b) before and after springback.

The plate shows a significant change in curvature due to springback (Figure 7a). The maximum height of the plate after springback of about 150 mm even exceeds the maximum height of the plate in scenario 2 of about 110 mm. The larger curvature can probably be explained by the fact that gravity in scenario 3 influences the curvature in the last bending triangle during leveling. This leads to a higher plastic ratio, which in turn results in a stronger curvature. With regard to the stresses before and after springback (Figure 7b), it can be recognized that before springback there is an loaded stress state, while after springback there is a balanced stress state. Accordingly, the stresses were relieved in the springback simulation by changing the geometry. The stress profile of scenario 3 after springback corresponds to scenario 2.

The simulation has shown that residual stresses in the material can lead to considerable springback when the load is relieved. However, the extent of the geometry change shown here is less noticeable in the real process. This is due to a multitude of aspects: In reality gravity continues to act on all individual parts cut from a heavy plate. More importantly, temperature ranges between 600 °C and 1000 °C are typical for hot heavy plate leveling. This allows softening mechanisms to take place in the material which lead to a reduction of stresses. This aspect is discussed in the following section.

3.4 Stress relaxation

Due to high temperatures in the production of heavy plates, stresses within the plate may be reduced during or after hot leveling. The reduction of stresses is thermally activated and based on creep, recovery and recrystallization processes in the material. Further detailed information on the decrease of stresses due to the above mentioned phenomena are summarized in the works of S. Vervynckt et al. [12].
In order to assess the potential influence of softening on the leveling results and on springback, an artificial decrease in stress before the springback simulation was explored using scenario 3. The softening in this case is approximated by reducing the amount of initial residual stresses σ_{res} by factors between 0 % and 100 %. The results are shown in Figure 8.

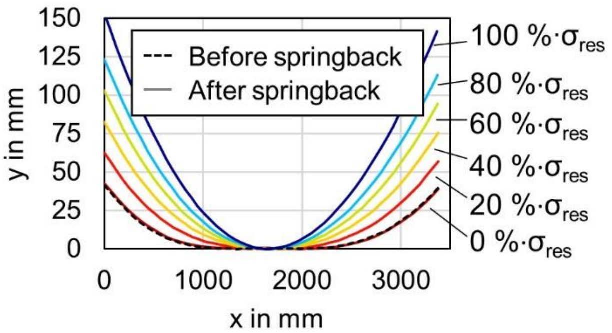

Figure 8. Geometries after springback with different levels of residual stresses.

It is obvious that the reduction of stresses has a significant influence on the level of springback. The lower the initial residual stresses σ_{res}, the lower the springback.

The extent to which the mentioned softening mechanisms actually have an effect on the reduction of stresses in industrial application is exemplified by a stress-relaxation experiment at a temperature of 800°C.
The resulting kinetics of the stress relaxation test are shown in Figure 9.

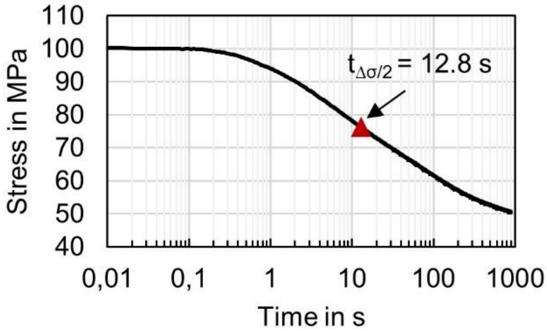

Figure 9. Stress relaxation of S355 at 800 °C.

The figure shows the typical course of such a test at high temperatures. Due to the rapid decrease of stress at the beginning of the test, the holding time is plotted logarithmically. It can be seen that the stresses decrease from 100 MPa to 50 MPa within 1000 seconds. Half of this reduction takes place after about $t_{\Delta\sigma/2}$ = 12.8 seconds. The test show that the majority of the stresses are relieved within a short time at high temperatures. Consequently, stress imbalances and curvatures caused by non-ideal roll-setups can be reduced to some extend by softening mechanisms.

4 CONCLUSION

In this paper, first the influence of the material parameters embedded into a FE-model for leveling on the resulting curvature after leveling has been analyzed. Furthermore the influence of gravity on the geometry and residual stresses has been investigated. In addition, the influence of softening mechanisms on the springback after leveling was evaluated.
The following conclusions can be derived from the investigations within this work:
With numerical simulations, it was demonstrated that even small deviations

from the correct material parameters (Young's modulus and initial yield stress) can lead to significant curvature after leveling when gravity is neglected.
Subsequently it was shown that material parameters, which lead to strong curvature without taking gravity into account, can result in mostly flat plates under consideration of gravity. In this case, however, strong residual stresses are present in the plate, which can lead to springback, for example during cutting. However, softening mechanisms present at high temperatures can significantly reduce these stresses.

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