



Towards hot levelling strategies for steel heavy plates: analysis of flatness evolution in accelerated cooling, hot levelling, and final air cooling via thermo-mechanical FE modelling

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Received: 2 November 2021 / Accepted: 21 January 2022 / Published online: 23 February 2022
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Abstract

In the production of heavy plates, the flatness of the products is an essential feature that must be set within narrow tolerances. Thus, the understanding of the flatness evolution throughout all relevant production steps in the rolling mill is paramount for high-quality products. It is known that most flatness defects arise either due to roll gap deviations in rolling or because of changing thermal conditions in the subsequent cooling processes. Severe defects induced during rolling are treated by a pre-leveller while the final heavy plate flatness after cooling is set in a dedicated hot leveller. Consequently, thermally induced defects need to be removed in this dedicated hot leveller as well. However, it is not yet feasible to model the flatness evolution throughout the relevant processing sequence consisting of accelerated cooling after hot rolling, hot levelling, and final air cooling. In order to close this gap and to analyse the process sequence with regard to flatness evolution, within this study, two cooling and a levelling model were developed and coupled with respect to thermal history, deformation, and residual stresses. These coupled thermo-mechanical finite element (FE) models were successfully applied to predict the flatness evolution in heavy plate production. Firstly, the formation of centre waves caused by inhomogeneous cooling conditions was captured. Secondly, the change in flatness during hot levelling was predicted. Thirdly, a transition from centre to edge waves was observed during final air cooling after levelling. This phenomenon (sometimes observed in industrial heavy plate production) was successfully reproduced in a sequence of coupled simulations for the first time. Finally, the hot levelling process was analysed via a parameter study to understand the root cause of this transition and to propose alternative hot levelling strategies that avoid it.

Keywords Heavy plate levelling · Accelerated cooling · Flatness defects · FE simulation · Through process modelling

1 Introduction

Heavy plates need to satisfy a plentitude of different requirements. On the one hand, the dimensions and flatness must be set within narrow tolerances. On the other hand, the mechanical properties, such as yield strength and tensile strength, must meet or exceed demanding specifications. These mechanical properties can only be set to a certain extend by multi-pass hot rolling directly, i.e. via strain hardening and

grain refinement due to recrystallisation. Instead, hot rolling is typically followed by pre-levelling and a complex heat treatment often also involving accelerated cooling (ACC) using water spray of varying intensity to quickly decrease the temperature of the plates. This process allows to control the phase transformations to bainite or martensite and thus set the final mechanical properties. ACC of heavy plates is a very delicate and challenging procedure where small deviations in the heavy plate's surface condition or the process control will inevitably lead to inhomogeneous conditions. This in turn typically causes temperature gradients that induce thermal stresses that, if exceeding a critical value, can result in flatness defects in the plates after cooling and potentially also in the final product.

Consequently, most heavy plates undergo hot roll levelling right after cooling to eliminate flatness defects induced by hot rolling and cooling and thus meet the tight flatness

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tolerances mentioned above. Levelling right after cooling, where residual temperatures from hot rolling of up to 750 °C still persist in the plates, is beneficial as the yield stress of the plates is reduced, and thus less levelling force is required. However sometimes, the levelled plates are flat after hot levelling, but temperature differences and residual stresses still exist across their length, width, and/or thickness. Under these conditions, additional thermal stresses can develop during final air cooling due to inhomogeneous shrinkage and if the critical stress for buckling is exceeded flatness defects can recur in the final plate.

Up until now, the complex interaction between thermal and mechanical stresses evolving in the plates during ACC, hot levelling, and final air cooling that can lead to manifold flatness defects has not been fully understood and coupled finite element (FE) modelling of the relevant processing sequence, where all relevant field variables are transferred, is not established yet. Hence, further insight into the conditions that induce these flatness defects and control their evolution is currently not available.

Accordingly, the aim of the present paper is to simulate the flatness evolution of a heavy plate throughout the processing sequence ACC, hot levelling, and final air cooling using a FE modelling scheme that enables the transfer of geometry, temperatures, strain, and residual stress in between the different models and simulations. The heavy plate prior to ACC is assumed to be flat and also free of residual stresses due to pre-levelling. The models proposed are validated using data from both laboratory trials as well as an extensive industrial database. To understand if residual stresses induced mechanically, by temperature gradients, or by a combination of both are crucial for the flatness evolution observed in industrial practice, four scenarios are put forward that allow for an isolated investigation of these factors. The coupled simulations are specifically used to analyse the transition of centre waves present after ACC to edge waves in the final plate after air cooling as this is sometimes observed in industrial practice and provides the opportunity to validate the prediction capabilities of the employed modelling. Finally, the results are reviewed to access in how far the coupled simulations can provide new insight and understanding into the hot levelling of heavy plates with thermally induced flatness defects.

2 State of the art

The flatness evolution in rolling and levelling has already been analysed in previous studies. Additionally, approaches for modelling flatness defects exist. This section first gives a definition of typical flatness defects and their well-known formation during rolling (Sect. 2.1). Then, the evolution of flatness defects throughout ACC (Sect. 2.2), hot levelling

(Sect. 2.3), and air cooling (Sect. 2.4) is discussed. FE-based approaches that enable the modelling of flatness defects (Sect. 2.5) as well as their elimination via levelling (Sect. 2.6) published in literature are summarised next. Finally, the current state of the art with regards to modelling flatness evolution is critically assessed (Sect. 2.7).

2.1 Definition of flatness defects and their formation due to rolling

In the production of heavy plates, the rolling process is primarily intended to define the dimensions of heavy plates and to a certain extent also the mechanical properties. ACC is used afterwards to further adjust the desired mechanical properties due to microstructural transformations.

Flatness defects may arise during both steps if processing conditions are not ideal. Sheppard and Roberts [1] provided a first comprehensive overview of existing flatness defects in rolled strip. Recently, some of the present authors [2] published a flatness defect catalogue associated with heavy plates as shown in Fig. 1.

The formation of defects due to rolling has already been thoroughly described: Kiefer and Kugi [3] stated that ski defects (Fig. 1a) are mainly due to asymmetrical conditions in the rotational speed during rolling as well as temperature or frictional differences between the upper and lower rolls and proposed an analytical modelling approach for ski defects, while Hyang Seo et al. [4] developed an FE model to predict ski defects in rolling. Mücke et al. [5] argued that longitudinal waves (Fig. 1b) occur when changing plastic stretching and compression along the length of the plate occur over the thickness. This causes oppositely directed longitudinal residual stresses on the upper and lower sides of the plate. These stresses are almost constant over the plate width. According to Behrens and Krimm [6], the aforementioned defects can be categorised as the so-called windable defects which can be easily eliminated by bending around one axis. Furthermore, Behrens and Krimm [6] presented additional

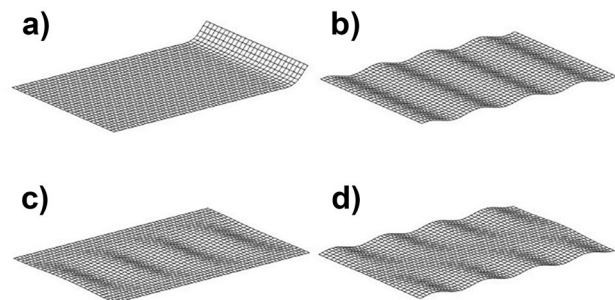


Fig. 1 Schematic flatness defects according to [2]: **a** ski defect; **b** longitudinal waves; **c** centre waves and **d** edge waves

flatness defects commonly observed such as centre waves (Fig. 1c) and edge waves (Fig. 1d) which are categorised as the so-called non-windable defects. Tran et al. [7] discussed that non-windable defects are usually caused by strong residual stresses which can be induced, for example, in the rolling process by inhomogeneous thickness reduction over the width. Besides inhomogeneous conditions during rolling, flatness defects can arise also due to thermal aspects, e.g. during cooling, as will be summarised in the following section.

2.2 Flatness defects during accelerated cooling (ACC)

To control microstructure and further enhance the material properties of the plates after hot rolling ACC via an inline device is a necessity for most plate producers [8]. ACC enables to significantly increase strength properties without lowering impact toughness or cold resistance [9]. Wang et al. [10] as well as Peregrina et al. [11] described that in the ACC process, flatness defects may arise due to inhomogeneous cooling conditions. For example, if the cooling at the edges is too large, the temperature at the plate’s centre will be higher than that in the edge portion. As a result, there is a temperature difference ΔT across the width. This results in a longitudinal compressive stress σ_L in the centre as thermal shrinking is correlated to the temperature via

$$\sigma_L = E \alpha \Delta T \tag{1}$$

where E is the Young’s modulus and α is the thermal expansion coefficient. This leads to centre waves, if the compressive stress in the centre exceeds the critical stress for buckling, see Fig. 2b. Vice versa, if the centre is overcooled, edge waves can occur, see Fig. 2b. According to Wang et al. [10], centre waves are less likely to be observed as their critical buckling stress is about nine times the stress required for edge waves.

According to Lee et al. [8], the incoming flatness is the most important external factor for uniform cooling in ACC, as the flatness will influence the trapping and flow of water on the plate.

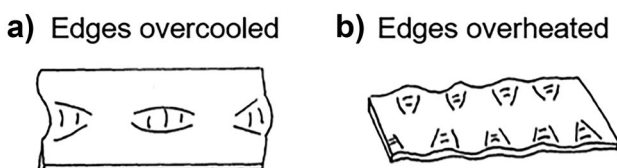


Fig. 2 Edge and centre waves due to inhomogeneous cooling conditions according to [10]: **a** Edges overcooled; **b** edges overheated

2.3 Flatness defect reduction during hot heavy plate levelling

In order to eliminate flatness defects caused by hot rolling or ACC, a heavy plate leveller is typically used, see Fig. 3. Among others, Silvestre et al. [12] described that in the levelling process, the plate with its defects is subjected to alternating elastic–plastic bending between the levelling rolls. Depending on the bending direction, plastic tension or compression occurs in the areas close to the plate’s surface.

The intensity of the levelling process is determined by the positions of the levelling rolls and is referred to as the so-called plastic ratio which allows an assessment of the percentage of the thickness that undergoes plastic deformation due to bending. According to Galdos et al. [13] and Cui et al. [14], a plastic ratio between 70 and 80% is recommended. However, the plastic ratio is generally not constant but can vary due to differences in flatness and residual stress over the plate’s length.

Liu et al. [15] as well as Park and Hwang [16] showed that two-dimensional curvatures can be easily eliminated via the levelling process. Behrens et al. [17] investigated the influence of edge and centre waves on a 21-roll levelling machine. Centre waves were completely eliminated in this test series but edge waves were generated both in the simulation and in the experiment, which was explained by non-optimal setups. Negami and Higo [18] investigated the influence of the wavelength of edge waves on the levelling result. Edge waves with different wavelengths between 500 and 2000 mm were investigated. It was shown that the wavelength has a great influence on the result. The larger the edge wavelength, the better the levelling result, which is described by the restraint of the waviness by the levelling rolls.

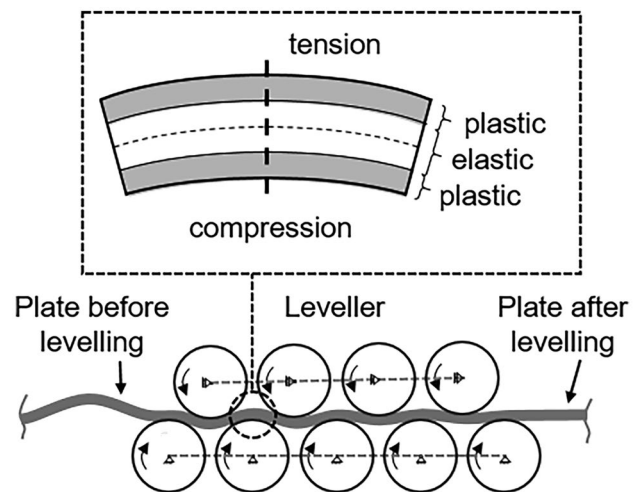


Fig. 3 Schematic 9-roll leveller

2.4 Flatness defects during air cooling

After hot levelling, the plate's temperature can still be > 400 °C and hence plates are air cooled to room temperature. Wang et al. [10] described that if temperature variations in transverse direction remain after levelling, the temperature decline and shrinkage of the plate during air cooling will vary with the local position even if the plate is flat and free of residual stresses after levelling. The difference in thermal shrinkage ΔL is directly proportional to the temperature difference of the plate's centre and edge via

$$\Delta L = L\alpha(T_C - T_E) \quad (2)$$

where L is the plate's length, T_C is the temperature in the centre, and T_E is the temperature at the edges.

Consequently, new thermal stresses are induced by the inhomogeneous shrinkage, and thus new flatness defects arise. However, these flatness defects are inverted when compared to the defects induced by ACC. For example, a centre wave caused by overcooled edges (see Fig. 2) during water cooling will transform into an edge wave after hot levelling and cooling to ambient temperature. This is illustrated in Fig. 4, where T_0 is the room temperature while T_C and T_E were introduced before.

According to Colás et al. [19], flatness defects may also arise without the use of ACC when the rolled plate cools down to room temperature: during this process the distribution of both temperature and microstructure will cause variations in the local contraction that the steel is subjected to, and will promote flatness defects.

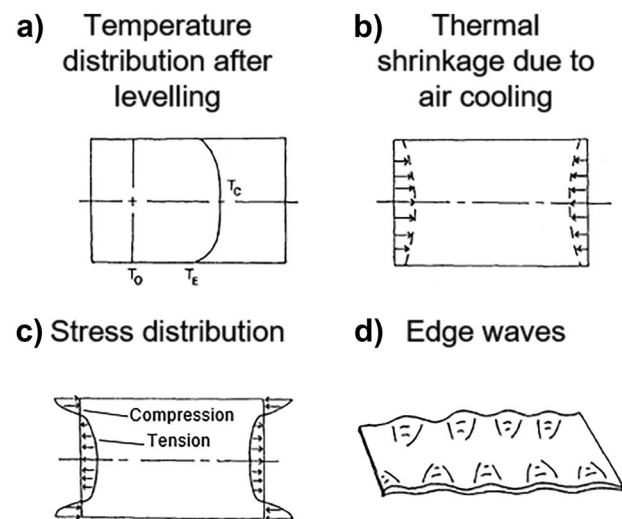


Fig. 4 Transformation of centre to edge waves in air cooling according to [10]: **a** temperature distribution after levelling; **b** thermal shrinkage; **c** stress distribution; **d** edge waves

2.5 Modelling of flatness defects via finite element method

In the following, different FE-based model approaches for the simulation of flatness defect and their evolution are summarised and subdivided into approaches for defects induced by cooling and approaches for defect evolution in levelling processes.

Wang et al. [20] established a thermal, microstructural, and mechanical coupled model for the prediction of flatness change of a steel strip during run-out table cooling using Abaqus. Within this model, stress gradients due to inhomogeneous cooling and its influence on the flatness are calculated. They concluded that flatness deviations will develop under transverse thermal differences. Cho et al. [21] used a similar modelling approach. When considering thermal, microstructural, and mechanical aspects, edge waves occurred due to strain gradients caused by temperature differences between edge and centre regions (edges cooler than centre). Weisz-Patrault and Koedinger [22] proposed an alternative numerical strategy to simulate an inhomogeneous cooling of a strip on the run-out table. The approach accounts for heat conduction coupled with metallurgical transformation and elastic–plastic calculation of residual stress evolution. Results show that cooling one surface faster than the other creates an asymmetry that is responsible for a bending moment which results in flatness defects such as a bow in the length or width direction. Wu et al. [23] designed a 2D model to analyse the temperature history, deformation, and phase transformation during a first laminar cooling and a second alternative water or air cooling. The model was able to predict different curvatures during the individual cooling steps.

The complex models mentioned above were designed only to investigate thermally induced flatness defects in isolation. For the investigation of the levelling process, flatness defects are generally modelled as geometrical deviations of the incoming sheet in order to avoid complex modelling of their formation via thermal or mechanical stresses: Trull [24] investigated non-windable flatness defects for a stretch bending levelling. The modelling of edge waves was done geometrically and without consideration of residual stresses. Similarly, Madej et al. [25] proposed a complex FE model for hot leveling of longitudinal waves incorporating a combined hardening model, but neglected residual stresses in the initial plate. As part of the investigation on levelling concepts for edge waves, Negami and Higo [18] also modelled the initial flatness before levelling geometrically. Finally, in the investigation of levelling ski defects, Hyung Seo et al. [4] numerically compared results based on a plate where initial deformation was induced via a three-roll bending process with a plate where the deformation was imposed geometrically without information on strain and hardening.

The results revealed that considering information about the deformation made the simulation of the levelling process more precise and reliable. Finally, Grüber et al. [26] showed that residual stresses after roll levelling of thin sheets can be predicted via FE models and even controlled if a roll leveller with sufficient degrees of freedom is employed.

The aforementioned literature shows that the modelling of flatness defects in cooling processes is possible but very complex. Approaches for modelling of the flatness defect evolution in levelling processes mostly rely on a purely geometrical representation of deviations for reasons of simplification, although there are indications that taking deformation into account leads to more precise results.

2.6 Modelling of the levelling process via the finite element method

In the following, different FE-based approaches for the levelling of flatness defects are summarised: Negami and Higo [18] used an explicit solver in Abaqus to investigate the influence of edge waves on the levelling result in a 8-mm-thick rolled plate. The rotation of rolls assumed to be rigid bodies transports the material through the machine. Silvestre et al. [27] designed a 2D model with 13 rigid rolls using MSC Marc®. Hexagonal elements with four integration points were used. In order to reduce the computing time, four elements were used globally over a sheet thickness of 2 mm, while additionally a local area with 16 elements over thickness was employed for more precise results. To further reduce computing time, the sheet was assumed to be static while the rolls move and rotate towards the sheet.

Trull [24] developed an Abaqus model and employed an implicit solver for the investigation of non-windable flatness defects by means of a stretch bending leveller. Reduced integrated shell elements with a size of 12 mm and a locally refined size of 2 mm at a sheet thickness of 1.5 to 3 mm were used. Only a small area was finely meshed and subsequently used to investigate stresses and strains. Levelling was performed by moving rigid rolls assumed to be frictionless over a fixed sheet. Chen et al. [28] developed a 3D thermo-mechanical coupled model to investigate the hot levelling process using MSC.Superform. The rolls were assumed to be rigid and symmetry was used to reduce the computational time.

The above-mentioned studies show that existing approaches for the FE modelling of the levelling process differ significantly from each other. Except for the use of rigid levelling rolls, general rules cannot be derived. The development of an FE model for levelling, which is one of the aims of this work, therefore requires a critical examination and adaptation of the numerical boundary conditions to the relevant process conditions.

2.7 Literature assessment

Based on the literature reviewed above, the state of the art with regards to analysing and modelling the evolution of flatness defects can be summarised as follows:

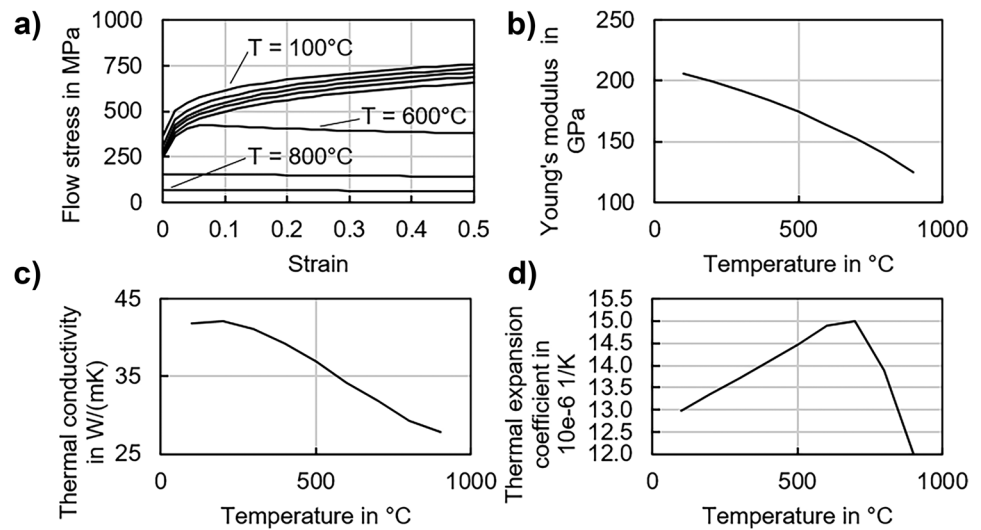
- While the formation and elimination of flatness defects by rolling and levelling on a mechanical basis is already well established, the levelling of thermally induced flatness defects is still insufficiently examined and only described on a phenomenological basis.
- To describe thermally induced flatness defects, several processing steps need to be considered. However, no study that comprehensively analyses, links, and models all the relevant processing steps of the heavy plate production chain exists.
- At the same time, the aspect of thermally induced flatness defects is of great importance since an inline cooling device is crucial for most plate producers to meet the current demands with regards to microstructural properties.

Only if the relevant processing sequence consisting of ACC, hot levelling, and air cooling could be described consistently via FE simulation, a prediction of the plate's flatness in each individual processing step and prospectively a comprehensive process optimisation would become feasible. Therefore, the aim of the work is to design an FE-based simulation scheme that couples the process steps: ACC, hot heavy plate levelling and final air cooling via transferring geometry, temperature, strain, and residual stresses. This scheme should enable a prediction of flatness evolution, an improved understanding for the factors governing this evolution, and, ultimately, novel concepts to further improve the quality of heavy plates.

3 Material and methods

After briefly introducing the material used in this study (see Sect. 3.1), the relevant processing sequence as well as the corresponding temperature and flatness evolution of typical heavy plates will be illustrated (see Sect. 3.2) based on data obtained in an industrial heavy plate rolling mill. To model this processing sequence, different types of cooling (see Sect. 3.3) and levelling (see Sect. 3.4) FE models as well as a specific model coupling and data transfer concept (see Sect. 3.5) are required that will be established next. The simulations introduced in this paper are designed to capture the stress- and temperature-induced evolution of the plate flatness. To comprehensively analyse the sensitivity of the flatness evolution to these features four different scenarios are laid out (see Sect. 3.6). Finally, the methodology

Fig. 5 **a** Flow curves determined via JMatPro in steps of 100 °C; **b** evolution of the Young's modulus; **c** thermal conductivity; **d** thermal expansion coefficient with temperature



for evaluating the flatness of the plates used in this paper is introduced (see Sect. 3.7).

3.1 Material

The material investigated in this study is the steel type API-X65MS-PSL2 which is typically used in hot rolled and subsequently cooled condition for welded and seamless large-diameter line pipes. The material data is derived based on the analysed chemical composition of the investigated material via the JMatPro software. Temperature-dependent flow curves, Young's modulus, thermal conductivity, thermal expansion, Poisson ratio, density, and specific heat capacity are considered. Although the calculated flow curves above 600 °C show no strain hardening, the data is sufficient for the current study as temperatures during hot levelling are mostly at or below 600 °C and during ACC the plastic strain is negligibly small (<0.01 based on simulation results presented later). Additionally, the initial yield at 700 °C when plastic

deformation first occurs in ACC is properly predicted by JMatPro. A selection of the temperature-dependent material data is shown in Fig. 5.

3.2 Flatness and temperature evolution in heavy plate production

The processing steps most relevant for the flatness of a heavy plate are summarised in Fig. 6 together with worst case plate flatness examples in these specific steps. The initial flatness of the plate is set by the hot rolling process. Height reduction is typically low in the last passes of the rolling schedule as these passes are crucially important to achieve adequate flatness. To set the mechanical properties, the majority of heavy plates is heat treated using ACC right after hot rolling. This process can deteriorate flatness if even the slightest inhomogeneity in cooling conditions occurs. Most often cooling is inhomogeneous in transverse direction, i.e. edges in rolling direction are overcooled, giving rise to centre waves as shown in Fig. 6. Hot

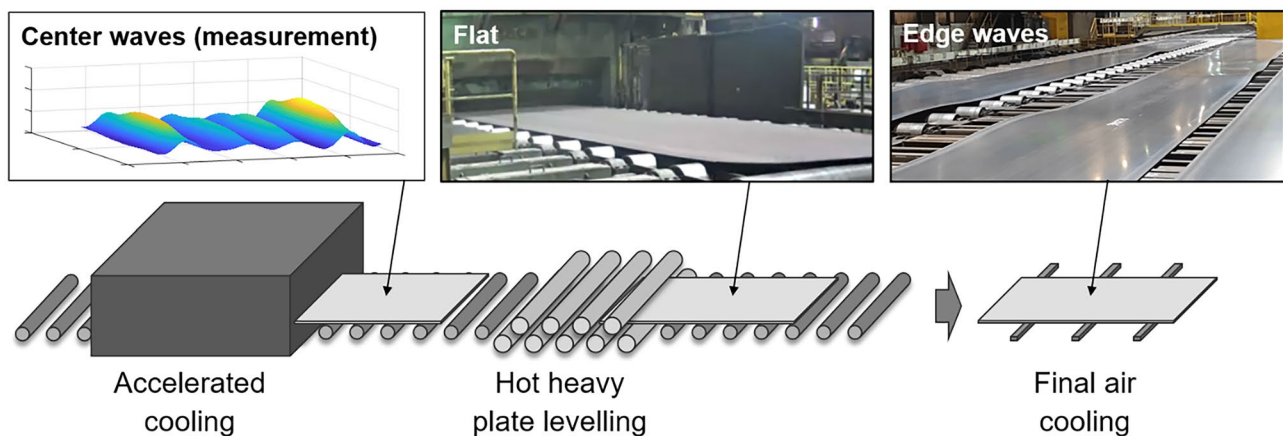


Fig. 6 Process steps most relevant for the flatness of heavy plates and a specific worst case flatness evolution example

heavy plate levelling is conducted right after ACC to eliminate potential flatness defects that have built up during previous processing steps. This leads to the plates being mostly flat again. Sometimes flatness defects recur while the plates are air cooling in a plate stack. As already discussed in the state of the art due to lower critical buckling stresses, these defects are often edge waves, also exemplified in Fig. 6. Thus, in an industrial plate mill, a transition of centre waves to edge waves can be infrequently observed in the processing sequence ranging from ACC via hot heavy plate levelling to final air cooling.

The evolution of the average temperature in a typical heavy plate through these steps is shown in Fig. 7 together with the surface temperature distributions of typical plates at three different points during production, as seen from above. Rolling mostly starts between 1100 and 1200 °C and often ends at about 750 °C. As the temperature has such a crucial effect on microstructure and mechanical properties, it is closely monitored throughout the production process using pyrometers and thermal scanners. For the same reason, temperatures and corresponding processing and cooling times are typically archived in a database. The temperature range most relevant to the current investigation starts at about 750 °C, which is a typical temperature right before ACC and ranges to 400 °C which is a typical hot levelling temperature for heavy plates exposed to accelerate cooling. In other cases, the hot levelling temperature can be higher.

In addition, the temperature range in air cooling (400 °C to RT) is relevant as stresses induced during production can cause flatness defects to recur.

The correlation between temperature differences within the plate and the flatness evolution touched upon above is best explained based on the specific heavy plates depicted in Fig. 7. After hot rolling, the temperature of the heavy plate surface is fairly homogeneous across all dimensions. The exact flatness at this point is unknown since no measurement is available. However, the plate is assumed to be mostly flat as a pre-leveller is used prior to ACC. After ACC, the thermal image indicates that the distribution of the surface temperature is no longer homogeneous and the edges are significantly colder than the centre. The corresponding flatness after ACC indicates strong centre waves. Afterwards, the plate is hot levelled until the centre waves have been sufficiently eliminated. The thermal image of the surface after hot levelling still shows colder edges. The plate is then stacked and air cooled to room temperature. During this final cooling process, edge waves appear.

3.3 3D FE model for the (water and air) cooling simulation

This section presents the FE model used to simulate the flatness evolution during plate cooling with inhomogeneous

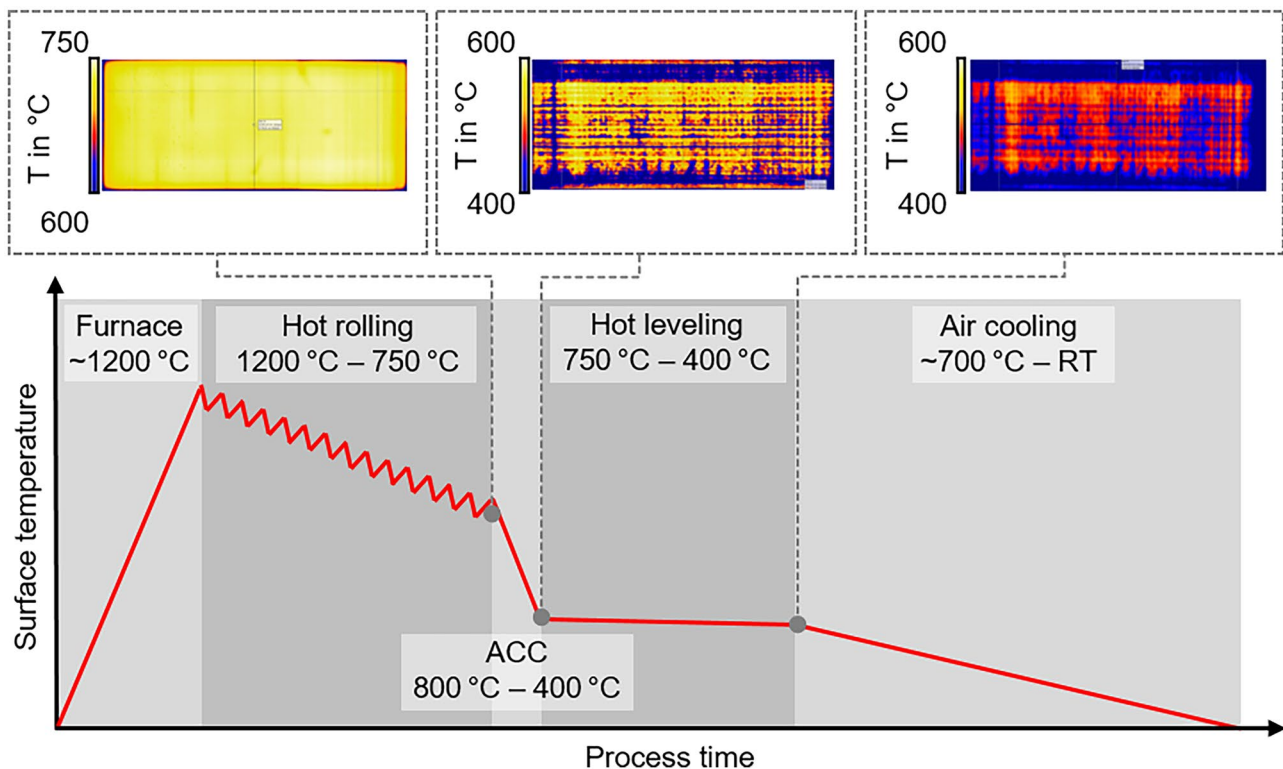


Fig. 7 Sketch of the surface temperature evolution of a typical heavy plate undergoing ACC and typical surface temperature variation in the corresponding process steps measured using thermal scanners

cooling conditions. Special emphasis in model design is put on the capability to model both the inhomogeneous ACC processes and the final mostly homogeneous air cooling to room temperature. In the following the required metal-physical and numerical boundary conditions are detailed. The FE model was implemented using the software package Abaqus CAE 6.14.

Initially the plate considered in the simulation is assumed to be perfectly flat with a homogeneous temperature of 900 °C. As stated above the plates are pre-levelled and the temperature is within the typical range after hot rolling and before ACC. In industrial production the length of the heavy plates ranges from approximately 6 to 30 m. In order to keep the computational time of the model within an acceptable range, the lower limit of 6 m is chosen here. The same holds for the plate's width of 2500 mm and its thickness of 10 mm, which are close to the lower limit of production. Apart from considerations regarding computational time, the thickness is deliberately chosen because according to Wang et al. [10] relatively thin sheets have a higher tendency to buckle due to the lower bending stiffness, which increases the chances of triggering this phenomenon. In summary the dimensions of the modelled plate are 6000 mm × 2500 mm × 10 mm in length, width, and thickness.

Based on a convergence study with respect to the stresses in x -direction as target value (proper stresses are the basis for the formation of flatness defects), the plate is meshed with elements having a size of 20 mm × 20 mm in plane and 2.5 mm in thickness direction. The Abaqus element type C3D8T (8-node thermally coupled brick, trilinear displacement, and temperature) is used. The objective is to compute thermal and mechanical equilibrium states due to inhomogeneous cooling. Therefore, the implicit solver Abaqus/Standard is used. As no contact with other bodies and also no large changes in geometry need to be considered, convergence of the implicit simulation is not a major concern. Gravity is deliberately neglected in this simulation so that all stresses can be released instantaneously. To prevent rigid body motion without influencing the simulation output, the plate is supported by two springs connected to ground with minimal stiffness. The thermal and mechanical properties of the considered steel-type API-X65MS-PSL2 have already been introduced in Sect. 3.1. The complete setup of the basic model is shown in Fig. 8.

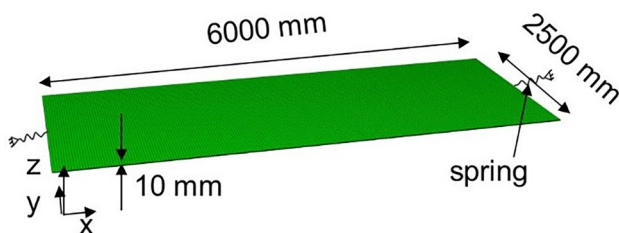


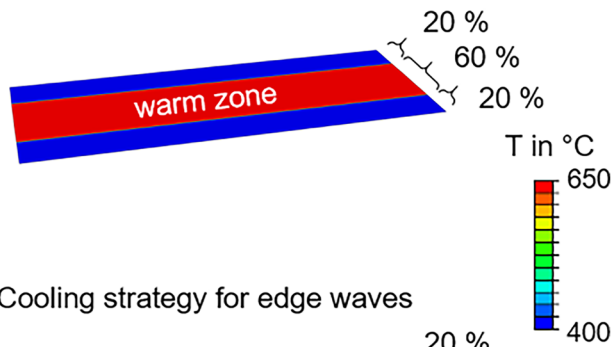
Fig. 8 Basic model for the cooling simulation

In order to induce residual stresses in the plate due to water cooling and hence potentially provoke flatness defects, the modelled plate is cooled inhomogeneously on purpose. As mentioned, this is infrequently also the case during industrial ACC. The model is designed in a way that it can induce both, edge and centre waves, in dependence of the temperature input. Based on the analysis of the surface temperature distribution measured in production, the plate is split into three thermal zones to represent inhomogeneous cooling conditions: The two edge zones and the centre zone are divided by a 20%–60%–20% pattern in width direction. Accompanying investigations have shown that other ratios of this slit are also feasible to cause flatness defects in the simulation. However, it is known from industrial practice that the extent of the defects is particularly high for the chosen split, which is beneficial for further investigations in this work. After ACC cold zones have a target temperature of 400 °C, whereas warm zones are only cooled to 650 °C. Temperature differences of up to 200–250 °C also match observations occasionally made in industrial practice, as visible in the thermal scanner measurements after ACC shown in Fig. 7. To create edge waves, the centre needs to cool down faster than the edges. Inversely, for centre waves, the edges need to cool down faster than the centre. Two examples used to create centre and edge waves in the modelled plate are shown in Fig. 9.

Starting from the initial temperature of 900 °C defined within the simulation as a *Predefined Field*, the entire surface of the plate is cooled down uniformly in the length direction to the target temperature of the respective zone. In the simulation, a linear decrease in temperature is applied over a pre-defined time period of approximately 10 s and thus comparable to the ACC process in industry. In Abaqus/Standard this is achieved via boundary conditions that set the target temperatures. N.b. the ACC is intentionally not represented in a physical manner. Instead, known initial and target temperatures, derived from measurements in industry, are imposed on the surface of the plate. This assumption allows a substantial simplification of the model as no complex heat exchange between surroundings, water, and plate has to be simulated. Even though some deviations from the industrial cooling process are to be expected, this approach mimics the phenomena causing flatness defect formation, as detailed in Sect. 4.1 later. Despite the simplifications, thermal heat conduction is still assumed inside the plate. This results in temperature gradients over thickness, as it is also the case in reality.

The modelling approach detailed here is reused later after levelling for the final air cooling of the modelled plate to room temperature. In this case, the target temperature of the entire plate surface is homogeneously set to 20 °C.

Cooling strategy for center waves



Cooling strategy for edge waves

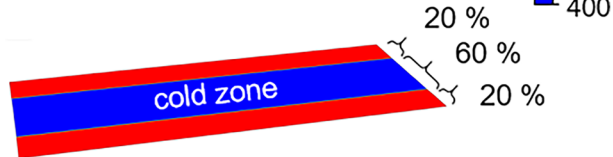


Fig. 9 Approaches for cooling strategies to simulate inhomogeneous cooling conditions

3.4 3D FE model for the levelling simulation

The 3D FE model used to simulate the levelling process and its boundary conditions are presented in the following. Again the software package Abaqus CAE 6.14 is used for the model setup. Due to numerous contacts between the plate and the leveller rolls, an implicit solver cannot be used here and the explicit solver Abaqus/Explicit is used instead. Nevertheless, the computational time is very high and, thus, the levelling analysis uses the purely mechanical solver instead of the thermo-mechanically coupled solver to cut down computational time. Note that the temperature distribution in the plate still results in stress gradients as the flow stress is temperature dependent. Thus, hot and cold zones introduced during ACC do influence levelling whenever this temperature field is transferred into the levelling simulation. In contrast, thermal effects occurring during the levelling process are not accounted for. However, assuming isothermal conditions is feasible, since the change in surface temperature during levelling is only about 20 °C in industrial practice for plates of similar dimension.

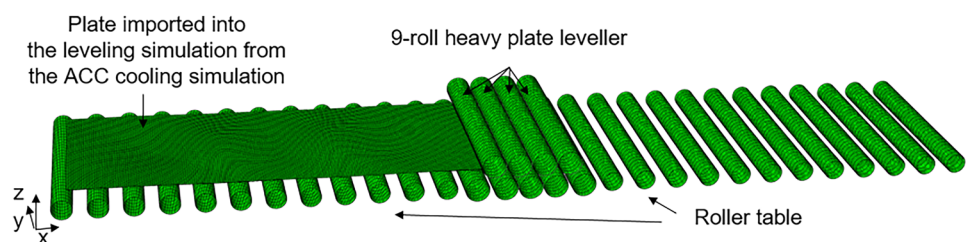
The 3D FE levelling model, shown in Fig. 10, consists of a roller table and a 9-roll heavy plate leveller with

dimensions equivalent to the leveller present in the industrial plant. Gravity is considered within the levelling model to ensure a realistic process where the plate's weight is pushing down onto the roller table and lower rolls. Again based on a convergence study considering both the plastic ratio and the plate curvature after levelling the mesh on the rolls and roller table consists of elements with 20 mm in circumferential direction and 100 mm in width direction. Abaqus/Explicit elements of type R3D4 (4-node 3D bilinear rigid quadrilateral) are used. To capture friction between plate and rollers, the conventional “Hard Contact” formulation was used in Abaqus/Explicit and the Coulomb friction coefficient was set to 0.2 as a sensitivity study showed no significant influence of the exact value on the levelling results. Furthermore, this friction coefficient is in line with investigations by Ulibarri Hernández et al. [29] that reported values of 0.17–0.35 for levelling of a TRIP steel.

At the beginning of the simulation, the roller table and leveller rolls start to rotate, so that the plate is transported through the leveller. The roll positions of the levelling machine are adjusted in such a way that a plastic ratio of 60% in the first bending triangle is realised. The required positions of the rolls are predetermined via a separate 2D controlled levelling simulation, which adjusts the roll positions automatically in dependency of the given input parameter so that (1) the given plastic ratio is achieved in the first bending triangle and (2) an initially flat rolled plate leaves the leveller flat again. Detailed information concerning this model and the procedure can be found in earlier works by some of the present authors [30]. The high computing times of about 2 weeks using 4 cores of a 12-core workstation (Intel(R) Xeon(R) E5-2643 v3, 3.40 GHz, 96 GB memory) allowed only a limited set of simulations. Based on the industrial experience that centre waves are more likely to be introduced during ACC of heavy plates, the levelling simulations conducted will be limited to this type of wave.

A direct validation of the FE levelling model is impossible since the exact roll positions of the leveller under load cannot be extracted from the industrial process control interfaces, the model is validated using the laboratory scale leveller at the Institute of Metal Forming instead. This leveller consists of 7 rolls with a roll diameter of 56 mm each and is shown in Fig. 11a. The levelling model introduced above (cf. Figure 10) was adapted to match the dimensions

Fig. 10 3D FE model of the leveller in industrial scale



of the laboratory scale leveller (Fig. 11b). The validation was then carried out using the conventional deep drawing steel type (DC01) with a thickness of 1 mm and furthermore was restricted to room temperature to protect the leveller. The material properties of DC01 were characterised experimentally in previous work at the Institute of Metal Forming by Grüber et al. [31] via cyclic tests in combination with inverse modelling. Roll positions to set a plastic ratio of 60% were again predetermined using the above-mentioned 2D controlled levelling simulation. For validation, the forces at the upper levelling rolls as well as the resulting curvature are used. Two tests based on identical levelling parameters (EXP1 and EXP2) were performed to increase the significance of the results.

A comparison of the levelling forces measured during the two experiments and the forces predicted by the 2D controlled levelling simulation used to determine the roller positions as well as the 3D levelling model incorporating these roller positions is shown in Fig. 11c. The general agreement in between the experiment and the 2D as well as 3D simulations is good. A detailed analysis is presented hereafter. The force prediction at the first upper roll (number 2) is very good with average deviations from the experiment of 1% and 2% for the 2D and 3D simulations, respectively. In contrast the average deviation is greatest at the second upper roll (number 4) with -12% for both simulations. At the third upper roll (number 6), the force accuracy of the 2D simulation is improved at -2% while the deviation in the 3D simulation remains similar at 10%. While the deviation at the second upper roll

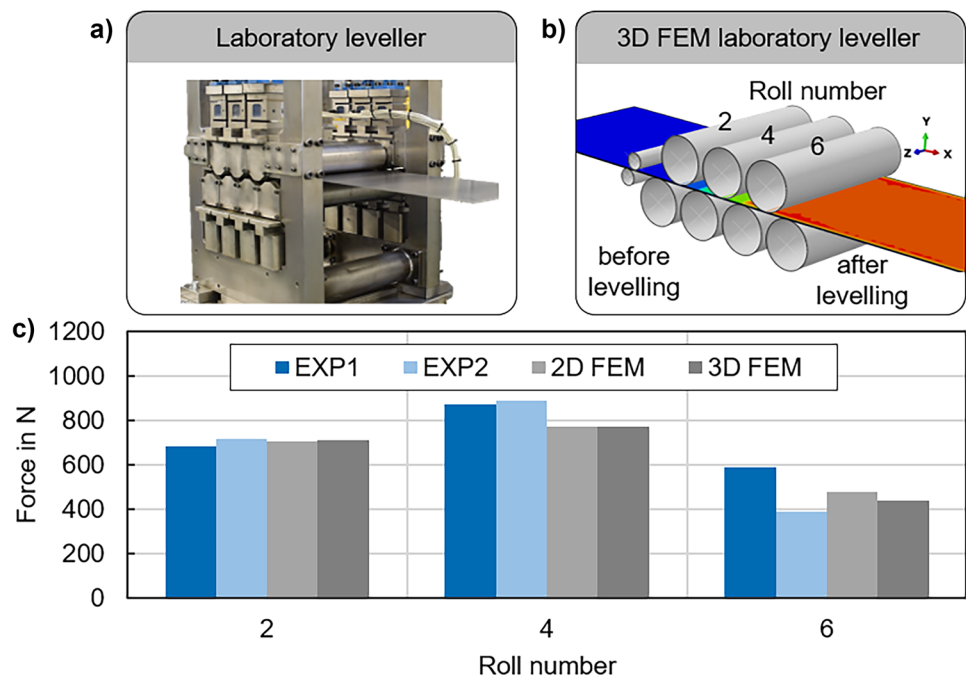
might be related to inaccurate modelling of the material's strain hardening, the differences between the 2D and 3D FE simulations can at least to some extent be explained by the fact that an implicit solver was used in the 2D case vs. and explicit in the 3D case.

The curvature after levelling was determined by fitting a circle to the digitised surfaces of the levelled sheets for both the experiments and the simulation. The average curvature of the experimentally levelled sheets is 0.018 m^{-1} . The curvature of the modelled sheet after the 3D levelling simulation is 0.016 m^{-1} . As the sheets are nearly almost flat both in reality and in the 3D simulation, this proves that the proposed model is capable of predicting flatness evolution in isothermal levelling with high accuracy. This is additionally supported by the levelling results at elevated temperatures presented in Sect. 4.2, even though a quantitative validation of these results is currently impossible as detailed earlier.

3.5 Simulation of the processing sequence via coupling of cooling and levelling models

To simulate the relevant processing steps, the models introduced in Sects. 3.3 and 3.4 need to be coupled and the computed state of the plate needs to be transferred accordingly as illustrated in Fig. 12. As mentioned in Sect. 3.3, the cooling model is used twice, once before and once after levelling. While the levelling simulation is isothermal, the relevant initial and final temperatures for both cooling models are known from measurements in industrial heavy plate

Fig. 11 **a** Laboratory leveller setup at the IBF; **b** 3D FE model of the laboratory leveller; **c** comparison of levelling forces for the steel DC01 measured in experiments and predicted via the 2D controlled and 3D FE models



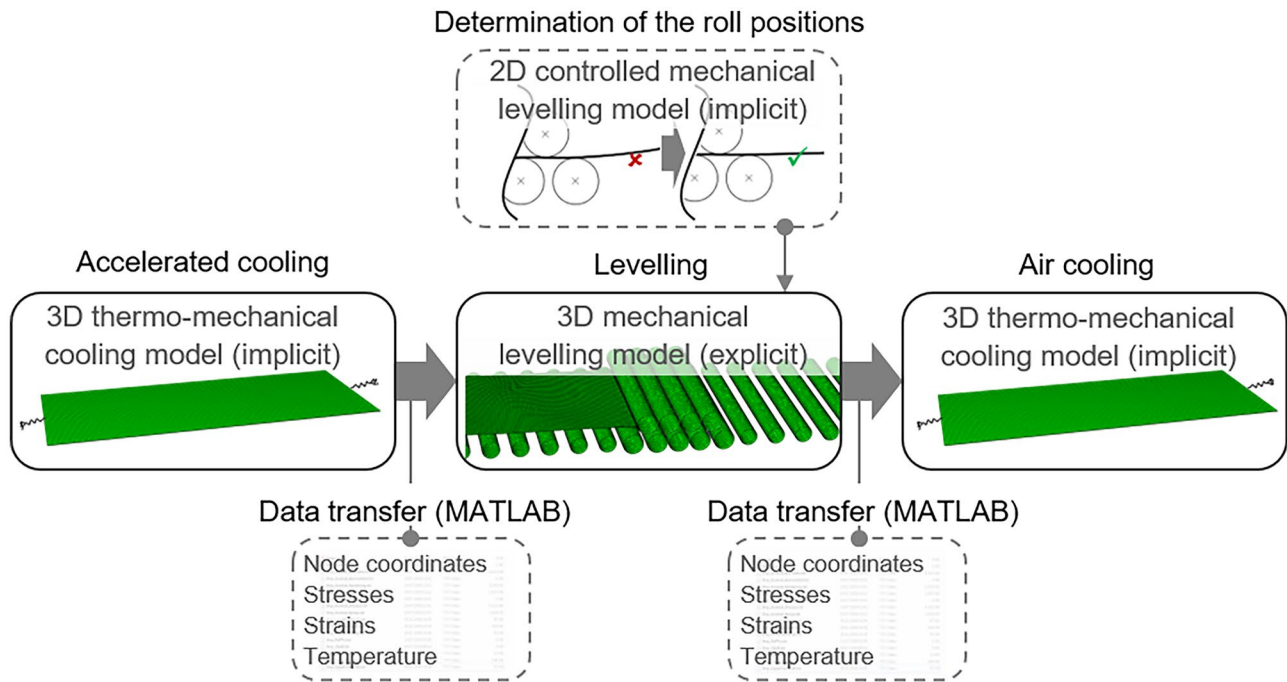


Fig. 12 Coupled 3D cooling and levelling models to capture the relevant processing sequence combined with a 2D controlled levelling model (see [30]) to predetermine the roll positions in levelling

production. Thus, it is possible to prescribe the surface temperature evolution of the plate considered and consequently modelling the thermal interaction of the plate with the environment or determining thermal boundary conditions is unnecessary in the present paper.

After the ACC simulation, the plate's state must be transferred into the levelling model. For this purpose, the plate's geometry, stress, and strain field and temperature field must first be exported from the cooling simulation and afterwards imported into the 3D levelling model.

First, the deformed geometry of the cooled plate is extracted using the node coordinates and the corresponding element connectivity. A custom script developed in MATLAB is used to convert the node and element information from the cooling simulation into an Abaqus CAE input-file compatible format and then write it to a CSV file. The data from this CSV file is then simply pasted into the Abaqus CAE input file of the 3D levelling model in order to integrate the deformed plate into the model as a "Part" of the assembly.

Then a similar procedure is used to transfer the information of the stress and strain as well as temperature fields that are afterwards reassigned to the corresponding elements and nodes using the *Initial Conditions* feature in Abaqus CAE. In the case of stress and strain, the entire tensors are transferred using the attributes *type = Hardening* and *type = Stress*. As described in Sect. 3.4, the target roll positions used in the 3D levelling model are computed via a separate controlled 2D levelling model (see [30]). After the levelling simulation

is finished, the plate's state is transferred back into the air-cooling simulation in the same way.

3.6 Four simulation scenarios to analyse the influence of stress and strain as well as temperature fields on flatness evolution

Stress and strain as well as temperature gradients inside a heavy plate are both assumed to greatly influence the flatness evolution during processing. Thus, the simulation scheme for the relevant processing sequence is designed in a way that it is possible to analyse the influence of stress and temperature fields on flatness evolution separately or in combination. To this end the following four scenarios are laid out: A *base* scenario that does not carry over stress and strain fields from the ACC to the levelling and further to the final air-cooling simulations. Instead stress and strain are reset to zero at the beginning of each simulation. The temperature field after ACC is reset to a homogeneous value of 650 °C but then transferred in between simulations. The *stress* scenario carries over the stress and strain field while again resetting the temperature field to 650 °C after ACC. On the contrary, the *temperature* scenario neglects stress and strain field but carries over the temperature distribution from ACC with zones of 650 °C and 400 °C, respectively. This inhomogeneous temperature field is then transferred in between all simulations. Finally, the *full* scenario carries over the stress and strain field as well as the inhomogeneous-zoned

Table 1 Overview of the scenarios investigated in the FE-based sensitivity analysis

Scenario	Initial stress and strain field	Temperature field after ACC
Base	Zero	Reset to homogeneous (650 °C)
Stress	Transferred	Reset to homogeneous (650 °C)
Temperature	Zero	Zones (650 °C/400 °C) transferred
Full	Transferred	Zones (650 °C/400 °C) transferred

temperature field. The initial state prior to ACC is generally assumed to be homogeneous and thus irrelevant for the scenarios, while in contrast the flatness defects caused by the zoned temperature distribution assumed in ACC are incorporated into every scenario via the node coordinates of the plate. All scenarios are summarised in Table 1.

The primary aim of the scenarios is to analyse which factor is decisive for the flatness result after levelling and final air cooling. Firstly, this allows to identify the design and parameters essential for a precise simulation of the considered processing sequence. Secondly, parameters paramount to an optimal process layout can hence be adapted to further improve the levelling results.

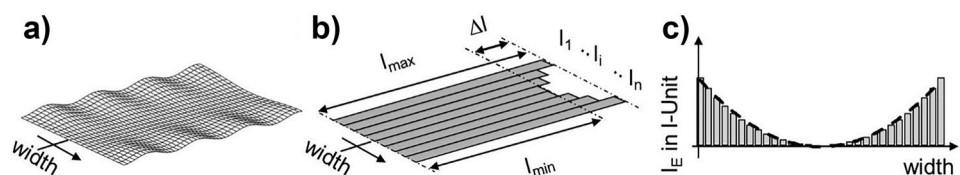
3.7 Methodology for evaluating the flatness of the plates

In order to quantify the flatness of the plates after each process step in the processing sequence, a strip length comparison over the width of the plate was carried out according to previous works of some of the present authors (see [2]). For that, the plate (Fig. 13a) was divided mathematically into strips in longitudinal direction over the width, as schematically illustrated in Fig. 13b. The length of each strip l_i is then divided by the length of the shortest l_{\min} strip according to Eq. (3):

$$I_E = \frac{l_i - l_{\min}}{l_{\min}} 10^5 \quad (3)$$

A factor of 10^5 is typically multiplied to ensure that one I_E represents an extension of 10 $\mu\text{m}/\text{m}$ (called I unit). I_E is also referred to as flatness index. The result is a distribution of I_E or I units across the width as shown in Fig. 13c. I units are most commonly used to evaluate the flatness quantitatively.

Fig. 13 Evaluation of the flatness: **a** edge waves; **b** strip length across the width of the plate; **c** I_E across the width of the plate



4 Results

This section presents the results obtained using the presented modelling approach. The aim is to simulate the relevant processing sequence to reproduce the sometimes observed transition from centre to edge waves as illustrated previously in Sect. 3 (see Fig. 6). The results of the individual process steps: ACC (4.1), hot levelling (Sect. 4.2) and final air cooling (Sect. 4.3) are introduced separately in the following sections. While not applicable for ACC in the levelling and air-cooling sections, the results are presented for all scenarios introduced in Sect. 3.6.

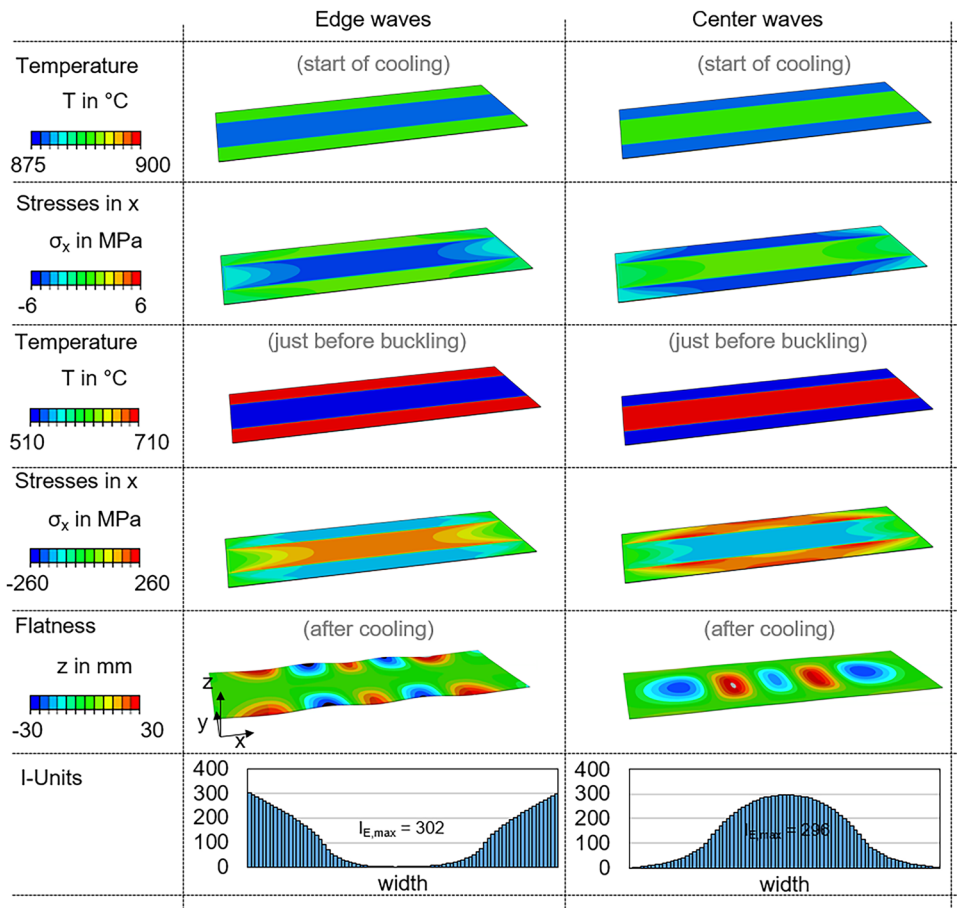
4.1 Flatness defects induced by inhomogeneous accelerated cooling (ACC)

The cooling model (Sect. 3.3) was first used to simulate the evolution of flatness during inhomogeneous ACC. The formation of waves is likely if temperature gradients in the plate are big enough. Thus, two cases were simulated starting from a homogeneous initial temperature of 900 °C that according to the zones defined in Sect. 3.3 is reduced to 650 °C and 400 °C, respectively. As discussed before an overcooled centre is expected to cause edge waves while centre waves should be induced by overcooled edges.

Figure 14 shows surface temperatures and surface stresses in x -direction for the edge and the centre wave cases right after the start of cooling and shortly before the plates buckle. After buckling, it is much more complicated to analyse stresses and just considering the plate's surface is not sufficient anymore as a stress gradient develops over thickness. In addition to stresses and temperatures, also the final flatness (displacement in z -direction) of the plates and the corresponding I_E values are shown.

According to the results, the temperature decrease in the individual zones was successfully preset and target temperatures were reached. Due to the inhomogeneous cooling, i.e. the temperature differences, stresses are induced immediately as can be seen from the first two rows. In the edge wave case, where the centre is overcooled, compressive stresses develop in the edge parts of the plate. In contrast, in the centre wave case, where the edges are overcooled, compressive stresses arise in the centre of the plate. Once the temperature difference reaches about 200 °C, the formation of edge

Fig. 14 Results of the cooling model after the ACC simulation



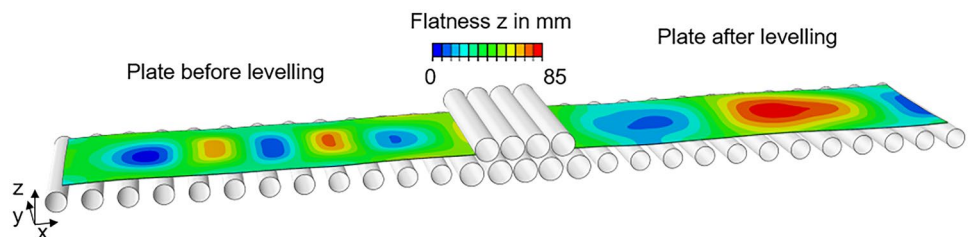
waves starts while the formation of centre waves requires a marginally greater temperature difference of 210 °C. Edge and centre waves occur in accordance with the stress state as predicted and show that the FE simulation is capable of capturing flatness defects caused purely by temperature differences in the plate.

The maximum wave heights are 60 mm for the edge wave case and 55 mm for the centre wave case, respectively. Edge and centre waves are also clearly visible from the characteristic courses of the I units. For the edge wave case, the strips at the edges of the plate are longer leading to larger I_E values at the edges compared to the centre. The opposite applies for the centre wave case. The maximum values $I_{E,max}$ are 302 for the edge wave plate and 296 for the centre wave plate, respectively.

4.2 Levelling of thermally induced flatness defects

After the ACC simulation, four different levelling simulations are conducted in accordance with the scenarios defined in Sect. 3.6. Therefore, the portion of the plate's state relevant to the respective scenario is transferred to the levelling simulation. In Fig. 15 the *full* scenario (cf. Table 1 in Sect. 3.6) where both the stress and the temperature field from ACC were carried over is shown. On the left the plate prior to levelling is shown, while on the right the levelled plate is depicted. This study is limited to the levelling of centre waves due to high computational cost and industrial relevance as already mentioned. However, the model could be applied to edge waves in much the same way.

Fig. 15 FE-levelling simulation of the ACC cooled plate with centre waves from the full scenario



The results clearly demonstrate that the hot levelling process changes the flatness of the plate. In the *full* scenario shown here, the five centre waves before levelling combine to two waves after levelling with an increased amplitude. Due to the variety of influencing factors (e.g. initial geometry, residual stresses, leveller setup), it is impossible to explain why the number of waves changes during levelling. Nevertheless, it can be assumed that the plate's stored energy is minimal in this configuration.

Figure 16 shows the results of the strip length comparisons (cf. Sect. 3.7) after levelling for all four scenarios (cf. Table 1 in Sect. 3.6). A maximum value of $I_{E,\max} = 296$ was recorded before levelling.

The results show that the centre waves generated during ACC prevail in all four scenarios. In the base scenario, where no data is transferred from ACC, a significant reduction of the maximum I unit value to $I_E = 150$ (corresponds to a decrease of 51%) can be achieved through levelling. Similarly, if only the temperature field from ACC is transferred (temperature scenario), a drastic reduction of the maximum I unit value to $I_E = 145$ (corresponds to a decrease of 53%) is achieved. In contrast, if only the residual stress field from ACC is transferred (stress scenario), a slight increase of the maximum I unit value to $I_{E,\max} = 329$ (corresponds to an increase of 8%) can be observed. Equally, if both the residual stress and temperature field are transferred (full scenario), the maximum I unit value slightly increases to $I_{E,\max} = 322$ after levelling (corresponds to an increase of 6%). In consequence levelling seems to be influenced mainly by the residual stress field.

4.3 Air cooling after levelling

After the levelling simulations, four separate final air-cooling simulations are conducted. The plate's state for the air-cooling simulation is taken from the levelling simulation

of the matching scenario. Additionally, only the part of the plate's state relevant to the respective scenario is transferred.

After simulation, a strip length evaluation for all scenarios was carried out, which is summarised in Fig. 17.

The results show that in the base scenario, where neither temperature nor stress field is transferred, centre waves still prevail after air cooling. The maximum I unit value of $I_{E,\max} = 150$ after levelling decreased slightly to $I_{E,\max} = 139$ after air cooling (corresponding to a decrease of 7%). The centre waves are also conserved after air cooling when only the stress field is transferred (stress scenario). However, here the maximum I unit value of $I_{E,\max} = 329$ after levelling increased slightly to $I_{E,\max} = 342$ (corresponds to an increase of 4%). In contrast if only the temperature field is transferred (temperature scenario), a transition of centre waves to edge waves can be observed. Furthermore, not only the position of the maximum I unit shifts but also the maximum value of $I_{E,\max} = 145$ after levelling increased to $I_{E,\max} = 317$ (corresponds to an increase of 119%), which is the largest change of flatness observed within this study. Finally, in the full scenario where the stress and temperature fields are transferred, a transition from pure centre to mostly edge in combination with minor centre waves can be inferred from the characteristic of I_E across the width. Also, the maximum I unit value of $I_{E,\max} = 322$ after levelling decreased to $I_{E,\max} = 170$ (corresponds to a decrease of 47%). In summary, a transition of wave types can only be observed during air cooling if the temperature field is transferred from levelling.

5 Discussion

In the following, the results described above are discussed with respect to some relevant aspects. Firstly, the capability to capture flatness defect generation via simulation is discussed. Secondly, the influence of stresses and temperatures on the coupled simulations of the relevant processing sequence is assessed. Thirdly, an in-depth analysis of the mechanisms

Fig. 16 Strip length evaluation over the plate's width for the four investigated scenarios (cf. Table 1 in Sect. 3.6) after levelling

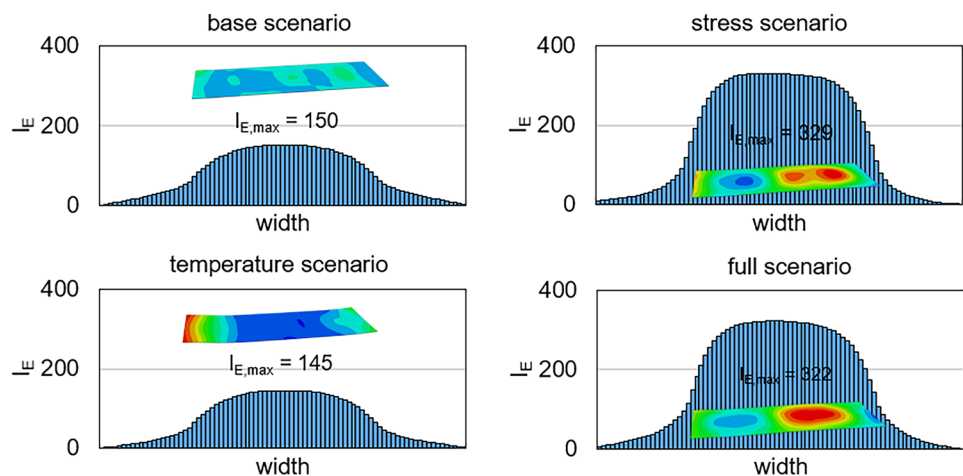
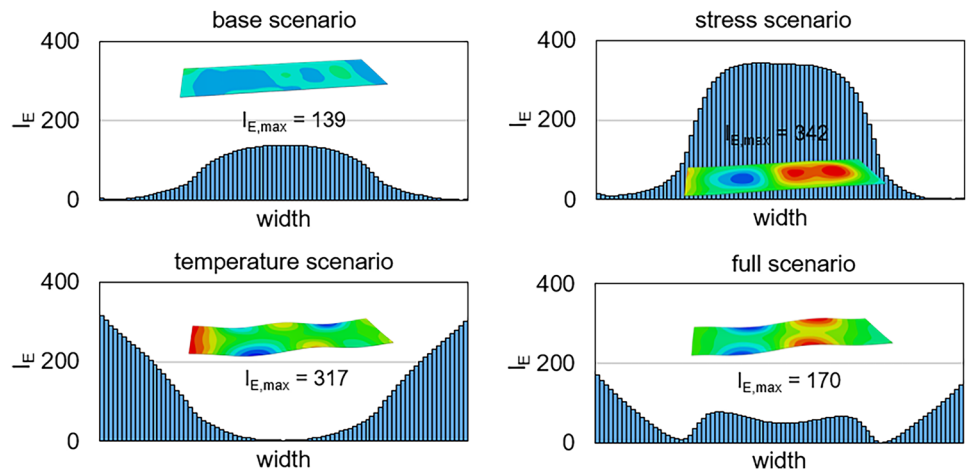


Fig. 17 Strip length evaluation over the plate’s width for the four investigated scenarios (cf. Table 1 in Sect. 3.6) after air cooling

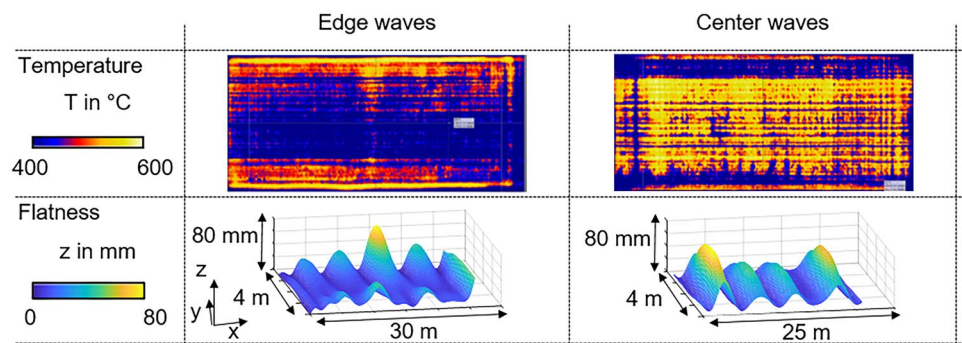


chasing a centre to edge wave transition during air cooling is presented. Finally, potentials for improved flatness in industrial hot heavy plate levelling practice are proposed.

5.1 Simulation of flatness defects induced by accelerated cooling (ACC)

The results presented in Fig. 14 clearly show that the generation of flatness defects in a level plate by unavoidable temperature inhomogeneity in ACC can be successfully captured using a thermo-mechanically coupled FE model. The temperature gradient in the plate induces stresses which ultimately lead to flatness defects once the critical stress for buckling is exceeded. This is caused by thermal shrinkage as the zones cooled down stronger experience a greater volume reduction, which consequently leads to tensile stresses in x -direction. If these stresses are high enough, they induce plastic deformation that persists even after the thermal gradients disappear. Furthermore, waves are generated in the undercooled zones due to compressive stresses once the critical stress for buckling is exceeded. Accordingly, it is obvious that edge waves are generated when the centre of the plate is cooled down faster and inversely centre waves are induced if the edges are cooled down faster. N.b., edge waves are induced easier as the critical stress for buckling is much higher in the centre than near the edges.

Fig. 18 Examples for thermal images and flatness after ACC of industrial plates



These observations are in line with results mentioned in the state of the art and previously published by Wang et al. [10]. They are additionally confirmed by data from industry: Fig. 18 shows two examples of surface temperature distributions with corresponding flatness taken from the industrial heavy plate mill data base.

As in the simulation, a direct correlation between surface temperature distribution and flatness can be observed. However, in production it is impossible to analyse the associated stresses as they cannot be measured online. Nevertheless, in the case of a cold centre, edge waves exist after cooling, while in the case of cold edges, centre waves are observed. These observations are in line with the simulation results and clearly give merit to the simulations even though a quantitative validation is impossible as the industrial plates have an unknown flatness and residual stress state after pre-levelling, greater geometrical dimensions, as well as slightly different absolute temperatures and surface temperature distributions.

5.2 Influence of stress and temperature field on the flatness evolution in levelling and air cooling

To visualise the influence that transferring or neglecting stress and strain as well as temperature fields has on the flatness changes in levelling and air cooling, the flatness

difference before and after the respective process step is used to define delta I units ($I_{E,n+1} - I_{E,n}$). If the delta I unit is positive, the I unit has increased from before (n) to after the process step ($n + 1$), thus representing worse flatness. Inversely, a negative delta I unit represents an improved flatness. Delta I units for all four scenarios are presented in Fig. 19, where the limits are chosen in accordance with the maximum changes in the process steps levelling and air cooling, respectively. Comparing the delta I unit plots in between scenarios reveals where transferring the stress and strain or temperature field in between process steps has an influence on flatness. The base scenario where the stress and strain fields from ACC are neglected and the temperature field is reset to homogeneous is used as the reference for the discussion hereafter.

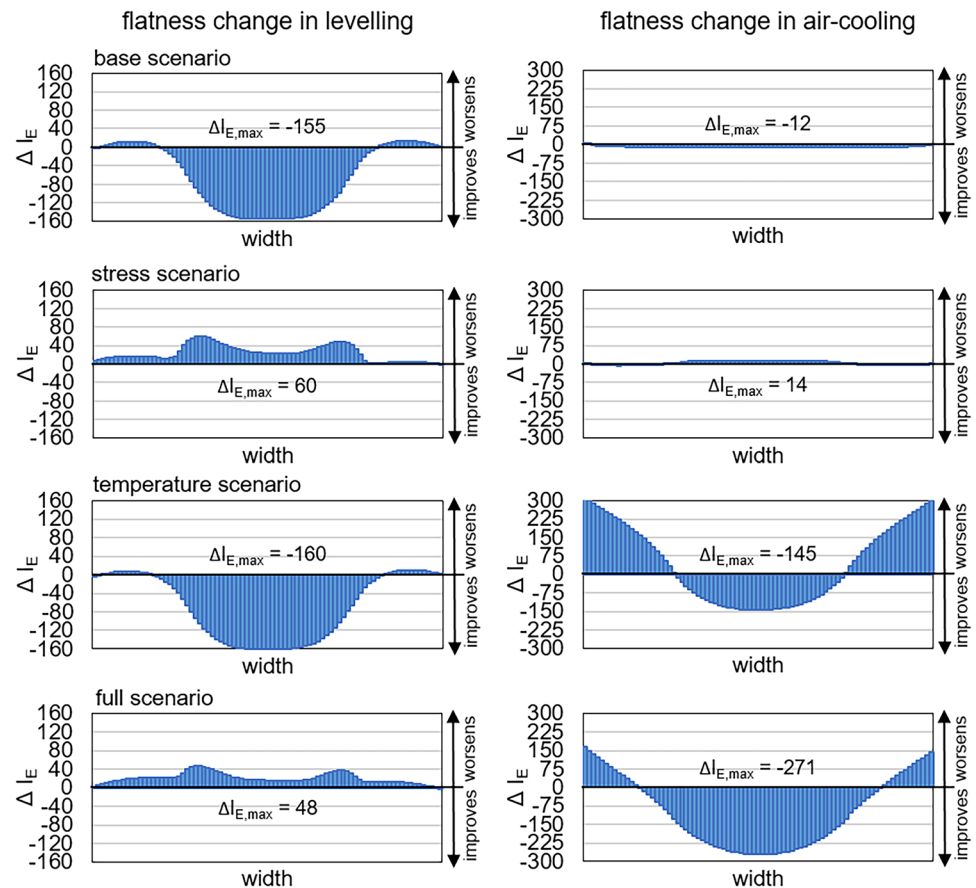
Focusing on levelling first, Fig. 19 illustrates that the flatness change in levelling is primarily influenced by residual stresses prior to levelling. The I units in the base and temperature scenarios where stress and strain from ACC are neglected significantly reduce by 155 and 160; i.e. the magnitude of the centre waves is halved. In contrast for the stress and full scenarios where stress and strain are carried

over from ACC, no such improvement is visible and instead the width and magnitude of the centre waves are slightly increased by 60 and 48 I units, respectively. Furthermore, the results clearly confirm knowledge from industrial practice that levelling plates with stresses inherited from ACC is much more challenging than levelling plates of comparable composition and temperature but without residual stresses.

The temperature field seems to play a minor role during levelling as the stress and full scenarios show almost identical results although the temperature field is inhomogeneous only in the full scenario. A similar conclusion can be drawn when comparing the base and temperature scenarios.

Focusing on the flatness change in final air cooling next, it is obvious that the flatness after cooling highly depends on whether a homogeneous or inhomogeneous temperature field is assumed. Scenarios temperature and full, where the temperatures are inhomogeneous, both show a transition from centre to edge waves during air cooling. However, there is a much stronger reduction of the centre waves in the full scenario (271 I units) than in the temperature scenario (145 I units). Thus, the residual stresses left from ACC and levelling seem to ease the transition of the waves in the centre

Fig. 19 Summary of flatness changes in levelling when compared to ACC and in air cooling when compared to levelling by means of delta I units



during cooling. In contrast, in scenarios base and stress, the flatness does merely change (12 and 14 *I* units, respectively) during air cooling. Thus, centre waves still exist and their magnitude remains mostly unchanged. The mechanisms behind the transition will be discussed in detail in Sect. 5.3.

Based on the above discussion, it can be concluded that residual stresses have a significantly higher influence on the levelling result than temperature inhomogeneity. Consequently, realistic stress and strain fields are required for a precise levelling simulation if substantial residual stresses prior to levelling are present. Exceptions may hold for scenarios at very high temperatures. Here it can be assumed that stresses are reduced due to softening mechanisms. Conversely, temperature inhomogeneity has to be considered to represent the air-cooling process accurately as the results are much more sensitive to the temperature field than to the stress and strain field. In summary, to capture the heavy plate hot levelling processing sequence, the transfer of stress, strain, and temperature fields throughout all simulations is advisable.

5.3 Analysis of the centre to edge wave transition during air cooling

Summarising the analysis carried out in Sect. 5.2 for all scenarios in Table 2, it is obvious that the transition from centre to edge waves can only be observed in the temperature and full scenarios. Thus, as mentioned earlier, temperature inhomogeneity during air cooling seems to be the determining factor, while the residual stress and strain field only influence the final flatness but do not trigger the transition.

For hot levelling and air cooling, unfortunately no further industrial data on flatness is available as the flatness of the hot plates is last measured after ACC. However, under similar air-cooling conditions, this transition of centre to edge waves is sometimes also observed in industrial processing, as shown before in Fig. 6 (see Sect. 3). To analyse the transition in more detail, Fig. 20 instead illustrates the shift from centre to edge waves during the air-cooling simulation in the full scenario. In particular, the evolution of temperature, flatness, and stresses over the air-cooling process are shown.

Figure 20a shows how the inhomogeneity in surface temperature distribution after levelling transforms into a homogeneous temperature field (1–3). At the same time, it

can be seen that centre waves are present as long as there is a noticeable temperature difference (1). As cooling progresses, the defects are initially reduced (2) until edge waves are finally generated (3).

In Fig. 20b stresses in *x* averaged over the plate thickness are shown. At the start of cooling (1), tensile stresses at the edges (position p_1) are still present together with compressive stresses in the centre region (position p_2). Observing the stresses at the edges and in the centre evolve with process time (2–3), it can be seen that there is a transition from tensile to compressive stresses (position p_1) and compressive to tensile stresses (position p_2). The transition can be mostly explained by the fact that at the start of air cooling, there is a larger temperature difference to room temperature in the centre (650 °C) compared to at the edges (400 °C). This results in larger thermal shrinkage in the centre of the plate. This causes strong tensile stresses in this area as the plate is stretched in the centre to comply with the surrounding material that is shrinking by a smaller amount. The plate’s edges are geometrically less constrained than the centre and thus the residual compressive stresses in the centre are readily converted into tensile stresses that now induce a compressive stress state at the edges. As expected, waves are then generated in regions where the compressive stresses reach the critical buckling stress.

5.4 Potential consequences for industrial hot levelling practice

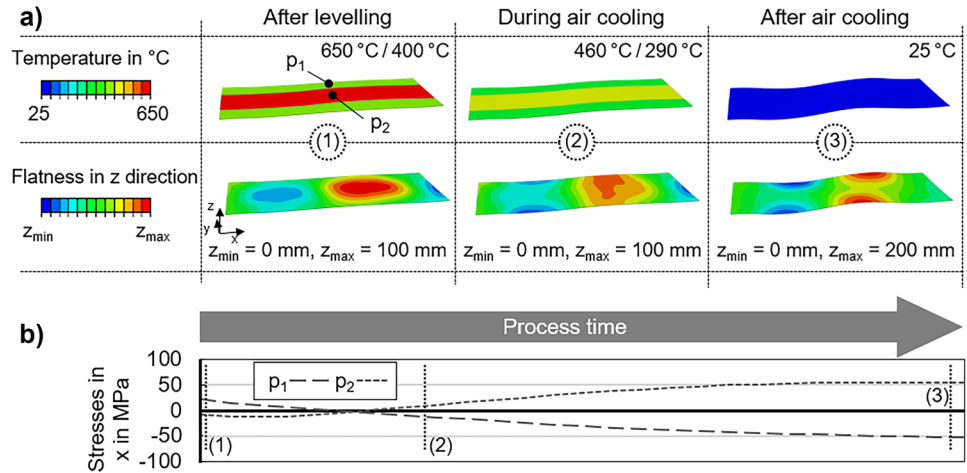
The tensile to compressive stress conversion on the edge discussed in Sect. 5.3 is probably alleviated by the fact that apart from the plastic deformation induced during inhomogeneous ACC, the plate’s centre is also elongated by plastic deformation in the hot-levelling process, which accordingly results in more absolute shrinkage in the centre region. To investigate this potentially detrimental effect of hot levelling on the flatness after final air cooling, additional simulations with different plastic ratios based on the full scenario were carried out.

The resulting flatness after levelling and air cooling is summarised in Fig. 21 for the plastic ratios of 0%, 60%, and 80%. The results clearly show two things: Firstly, an increase in levelling intensity promotes centre waves. The plastic ratios of 60% and 80% result in *I* units of 322 and 480, respectively, and thus both lead to stronger centre waves than prior to levelling (*I* unit of 296). Secondly, levelling greatly promotes the formation of centre waves overlaying the edge waves that inevitably form due to the mechanism discussed in Sect. 5.3. The centre wave *I* units are 20, 77, and 233 for the plastic ratios of 0%, 60%, and 80%, respectively. At the same time, the edge waves only slightly decrease in intensity. Thus, levelling cannot prevent the centre to edge wave transition as this is controlled by the temperature inhomogeneity

Table 2 Summary of the simulation setup required to reproduce the centre to edge wave transition

Scenario	Initial stress and strain field	Temperature field after ACC	Wave transition
Base	Zero	Reset to homogeneous	No
Stress	Transferred	Reset to homogeneous	No
Temperature	Zero	Zones transferred	Yes
Full	Transferred	Zones transferred	Yes

Fig. 20 Transition from centre to edge waves during air cooling in the full scenario: **a** temperature and flatness evaluation; and **b** thickness averaged stresses in x-direction over process time

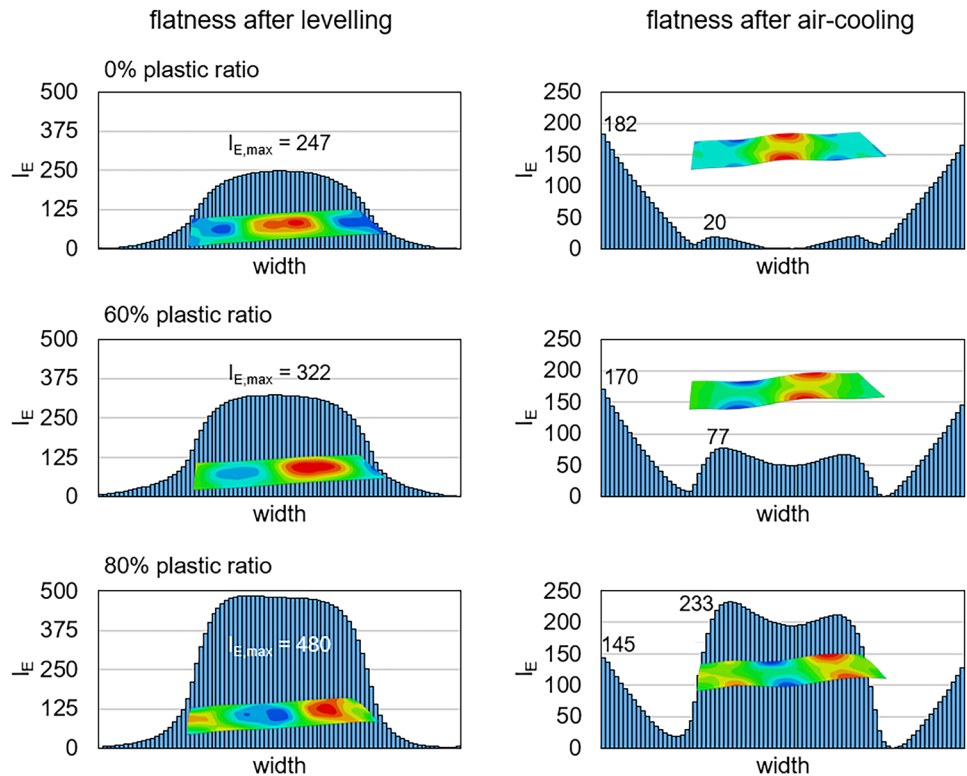


in the plate alone but instead seems to worsen the situation by causing superimposed centre waves that increase in amplitude with levelling intensity.

Based on the simulations, it seems advisable to restrict the hot-levelling intensity to the least possible amount required in production. Conventional hot levelling seems

unsuited and levelling could only help to eliminate thermally induced flatness defects once it becomes feasible to selectively level only narrow strips instead of the whole plate. Instead, emphasis should be put on improving the thermal homogeneity of the plates as much as possible.

Fig. 21 Flatness after levelling with different plastic ratios and after subsequent air cooling in the full scenario



6 Conclusion and outlook

In this paper, the processing sequence, ACC, hot levelling, and final air cooling, was successfully modelled via numerical simulation. Thereby, for the first time, the generation and evolution of thermally induced flatness defects were analysed in all relevant segments of the production chain of heavy plates. The following conclusions can be drawn from the investigations within this work:

- The investigation successfully modelled the generation of flatness defects in ACC via a 3D thermo-mechanically coupled FE simulation. The results confirm previous knowledge from literature and industrial practice that temperature inhomogeneity across the plates width caused by inhomogeneous ACC can lead to flatness defects. Overcooled edges lead to centre waves, whereas an overcooled centre leads to edge waves.
- In hot heavy plate levelling simulations, the residual stress and strain field have a dominant influence on the levelling results in terms of flatness. In this study, the maximum I unit of the stress scenario (329) is more than twice the value of the base scenario (150) after levelling. Accordingly, stress and strain within the plate need to be transferred from previous production steps for an accurate levelling simulation whenever residual stresses are present. However, flatness after air cooling is much more sensitive to temperature inhomogeneity. More specifically, the base scenario's maximum I unit (139) is less than half the value of the temperature scenario's maximum I unit (317). Thus, when analysing coupled levelling and cooling processes such as in heavy-plate production FE-simulation schemes should enable stress and strain as well as the inhomogeneous temperature field transfer.
- As known from industrial practice in air cooling after hot levelling, a flatness defect transition sometimes occurs. In this study the transition of centre to edge waves caused by temperature differences present after hot levelling was successfully modelled. The mechanisms involved were informed based on the simulation results: Thermal shrinkage in the centre of the plate with initially higher temperature induces compressive stresses on the edges that cause edge waves once the critical stress for buckling is exceeded. This process is further facilitated by residual stresses left from ACC. Prevailing flatness defects after air cooling can be expected for all plates with extreme temperature inhomogeneity.
- For the first time the influence of hot levelling on the centre to edge wave transition was investigated via numerical simulations. It was found that hot levelling cannot prevent the transition as it is driven by the temperature inhomogeneity alone. However, higher levelling intensity

has a negative impact on the amplitude of prevailing centre waves after air cooling. This study found a more than ten times increase (20 vs. 233) in the maximum I unit in the plate's centre when increasing the plastic ratio from 0 to 80%. Thus, it is advisable to restrict the intensity of hot levelling to the least possible amount required for safe processing of the heavy plates. To counteract the flatness defects, improved temperature homogeneity in ACC seems the most efficient means.

To obtain fully quantitative instead of qualitative results in the future, the thorough process modelling could be further enhanced: if sufficient computational power is available, the plate geometry could be increased to match the plates in production. Also, the cooling zones could be modified to better capture the transition from cooled to overcooled. Additionally, the prescribed surface temperature evolution could be replaced once the heat transfer coefficient in cooling is known. Furthermore, the model could be adapted to represent continuously cooling from head to tail as performed in industry. This would induce additional stress gradients in the plate's length direction. Finally, softening mechanisms at elevated temperature (e.g. recovery and recrystallisation) are expected to cause a reduction in residual stress. This has not been considered so far, but might have an impact on the magnitude of the flatness defect.

Acknowledgements The authors of the IBF would like to thank "AG der Dillinger Hüttenwerke" for the excellent collaboration, support, scientific exchange, and the provision of large amounts of measurement and process data.

Author contribution Conceptualisation, M. Laugwitz and J. Lohmar; methodology, M. Laugwitz, J. Lohmar; Validation, M. Laugwitz, M. Jochum, and T. Scheffer; software, M. Laugwitz; writing – original draft, M. Laugwitz and J. Lohmar; writing – review and editing, J. Lohmar, M. Jochum, and T. Scheffer; visualisation, M. Laugwitz; supervision, J. Lohmar; project administration, M. Jochum and T. Scheffer; resources, M. Jochum and T. Scheffer.

Funding Open Access funding enabled and organized by Projekt DEAL.

Availability of data and material The data relevant to this study is disclosed within the manuscript.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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