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On Considering the Influence of Kinematic Hardening in Finite Element Simulation of Hot Levelling of Structural Steel Heavy Plates

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Abstract. Flatness is an important quality parameter of heavy plates and it is generally achieved through cyclic elastoplastic deformation of the plate in a hot roller leveller following the rolling and cooling processes. To investigate and optimize the hot plate levelling (straightening) process, Finite Element (FE) simulations are widely used. Generally, flow curves with isotropic hardening are used for hot plate levelling simulations. However, the plate material might exhibit kinematic hardening, due to the load reversal that is seldom considered due to laborious high temperature cyclic material characterization. The current work aims at understanding the implications of considering kinematic hardening within hot heavy plate levelling simulations. Hot uniaxial and cyclic material characterization of S355 steel at 1000 °C is performed and the corresponding stress-strain curves are extracted. Using an inverse modelling technique, the associated isotropic and kinematic hardening models are calibrated. The cyclic data showed that the S355 steel exhibits kinematic hardening and the Chaboche kinematic hardening model is suitable to model this behaviour. Hot levelling simulations of plates with isotropic and kinematic hardening models showed a noticeable difference in the roll reaction forces and local curvature of the plate during the process while the resulting flatness of the final plate is not very sensitive to the material model for the investigated scenarios.

Introduction

Flatness is an important parameter used to define the quality of heavy plates. It quantifies how closely the final plate resembles a perfect plane. In general, heavy plates exhibit windable or 2D defects (ski, bow, curl and gutter) and non-windable or 3D defects (centre, edge and quarter waves) of varying magnitude due to non-uniform deformation occurring during the rolling and cooling processes [1]. Improving the process conditions in these processes can minimize the flatness deviations to a certain extent but seldom entirely [2]. Therefore, hot levelling is carried out, where the defective plate passes through a series of alternately arranged rolls as shown in Fig. 1a.

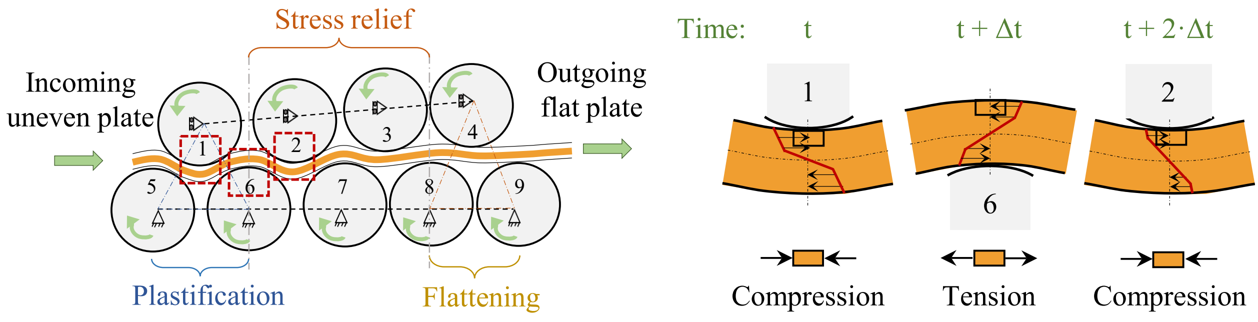

Fig. 1 (a) Principle of hot heavy plate roller levelling and (b) tension-compression cyclic loading experienced by the plate in the levelling process

Nowadays, FE simulations are widely used to design the levelling setup in terms of roll positions and reaction forces and to optimize the final plate flatness [3]. In this context, a suitable material model is of great importance. Since the longitudinal fibres of the plate undergo cyclic tension-compression deformation under alternating bending load imposed by the rolls as shown in Fig. 1b, the plate material might exhibit kinematic hardening, where its yield stress decreases with reversal of loading direction [4]. The current study investigates the extent of kinematic hardening the S355 structural steel exhibits at high temperatures and if it should be considered in the simulation of the hot heavy plate levelling processes. Especially the influence of kinematic hardening on roll reaction force, plate shape during levelling and plate flatness after levelling of the structural steel S355 is studied.

State of the Art

Isotropic, kinematic and combined hardening. While their actual deformation behaviour can be more complex, it is often sufficient to characterize metals in terms of isotropic hardening, where the initial yield stress σ_0 is assumed to increase with plastic strain irrespective of the loading direction. Such an isotropic hardening model is schematically shown in the Fig. 2a. Upon load reversal after initial hardening from yield strength σ_0 to forward yield stress σ_F, the magnitude of yield stress does not change and the material re-yields at $-\sigma_F$,. However, in reality, metals such as steels or aluminium alloys exhibit kinematic or combined hardening under reversed loading conditions. In kinematic or combined hardening, the material begins re-yielding at a yield stress -σ_R, whose magnitude is lower than the forward yield stress σ_F. In purely kinematic hardening a lower yield stress occurs upon load reversal but the amount of hardening usually does not vary with the number of load cycles as schematically shown in Fig. 2b. In combined hardening, as shown in Fig. 2c, the yield stress lowers with every load reversal but gradually increases with the number of cycles.

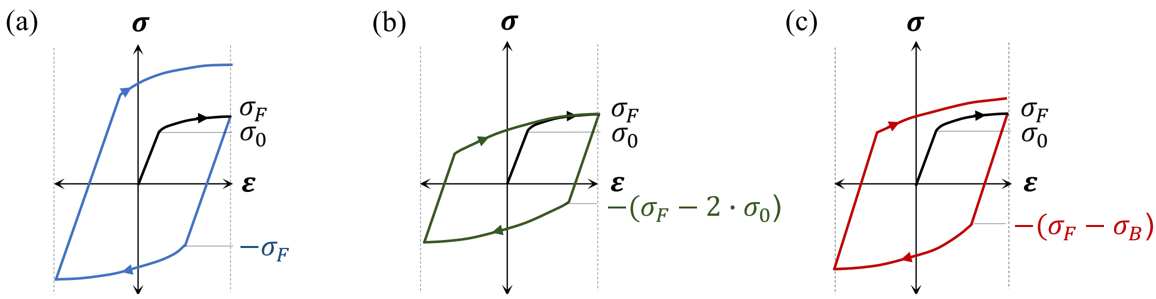

Fig. 2 Schematic of the evolution of yield stress for (a) purely isotropic (b) purely kinematic and (c) combined isotropic-kinematic hardening upon reversed cyclic loading

Kinematic and combined hardening frequently occur in steels at room temperature and are quantified using cyclic testing as already discussed, for instance by Silvestre et al. [5]. In contrast, the cyclic deformation behaviour at elevated temperatures is not extensively characterized. Research conducted by Kostryzhev [6] shows that kinematic hardening (or the so-called Bauschinger effect) in microalloyed steels also exists at high temperature. It is influenced by the dislocation creation, orientation, movement and obstruction due to grain boundaries and precipitates [6]. These dislocation mechanisms also occur in the austenitic phase of S355 structural steel at 950-1050 °C [7]. This implies that the kinematic hardening can occur in S355 and the current study focuses on this in the temperature and strain regime that is most relevant for hot plate levelling.
Material models for description of kinematic and combined hardening. Several existing material models can mathematically describe the lower yield stress during kinematic and combined hardening [8]. The lower yield stress during kinematic hardening can be modelled with the help of back-stress tensors. The classical Chaboche nonlinear kinematic hardening model (1975) for instance is based on the Armstrong-Frederick law and includes multiple back-stress tensors [9]. This kinematic hardening model was later modified by including isotropic hardening variables capturing exponentially increasing yield stress as a function of strain-memorization, resulting in the Chaboche combined

hardening model (1979) [9]. Later, in [10], Lemaitre et al. proposed further models for scenarios involving complex rate-dependent material behaviour and cyclic viscoplasticity, today referred to as Lemaitre-Chaboche (1990) model. This is important since cyclic viscoplasticity is sometimes observed in metals even at room temperature. Nowadays, the Chaboche type kinematic and combined hardening models are widely used as they can precisely model the non-linearity of the stress-strain loop, reduced yield stress at load reversal and permanent strain offset observed for some metals.

Material models used for levelling simulations. As mentioned before, metals at room temperature exhibit kinematic hardening and therefore, cold strip levelling simulations are mostly performed based on material models incorporating a kinematic hardening component. For example, the nonlinear Chaboche kinematic hardening model was used by Garcia et al. [11] for simulation of tension levelling of 1 mm thick DP1000 steel. Silvestre et al. [12] used Chaboche combined hardening model for roll levelling of 2 mm thick MS1200 and DC04 steel strips. Galdos et al. [13] used a Chaboche-Lemaitre combined hardening model for the simulation of levelling 1.2 mm thick Fortiform 1050 steel strip. In these studies, the kinematic and combined hardening models resulted in lower roll reaction forces and through thickness stresses in the strips compared to an isotropic hardening model. In another study [14] related to levelling of TRIP700 steel strip, Silvestre et al. showed that the number of cycles of stress-strain data used for calibration of the Chaboche-Lemaitre combined hardening model has a negligible influence on the simulated stresses, strains and levelling forces. While the combined and kinematic hardening models did not diverge much, an isotropic hardening model again resulted in significantly different roll reaction forces.

Unlike thin strips, levelling of heavy plates is performed at high temperatures typically ranging from 600 to 850 °C but sometimes as high as 1000 °C [2] depending on the material and thickness. At elevated temperatures strain rate dependence and cyclic viscoplasticity [10] can influence the material behaviour. Nevertheless, in levelling simulations, kinematic hardening and the strain rate dependence are mostly unconsidered and isotropic hardening models are used instead. This is due to two main reasons: Firstly, with increasing temperature, yield stress and strain hardening of steels generally decrease, as shown for example by Hosseini et al. [15]. Therefore, it is generally assumed that any hardening model gives similar results and strain rate variations in the process are minor. Secondly, cyclic material characterization and modelling procedures are complex compared to uniaxial characterisation and thus often omitted at elevated temperatures. An exception is the study of Madej et al. [16] related to heavy plate levelling of low carbon steel at 650 °C that focused on the optimization of the leveller setup. Using simulations based on cyclic material data at a constant srain rate of 0.1 s^{-1}, they suggested that a combined hardening model should be used instead of a simple isotropic hardening model. Similarly, in an RFCS project report [2] related to optimisation of plate flatness, several levelling processes were investigated. Therein, 5-roll levelling of a Weldox 960 structural steel plate at 850 °C was simulated with isotropic and kinematic hardening models calibrated based on material data at a constant strain rate of 0.1 s^{-1}. Similar curvature and plastification pattern of the plate were reported, but lower plastic strain levels were observed when a kinematic hardening model is used. Furthermore, in order to understand the stresses and strains, 11-roll heavy plate levelling at 900 °C was simulated with isotropic and kinematic hardening models. Here, very small differences in the resulting plate shape and the stresses were observed.

Summary of literature review and problem statement. The majority of research was focused on the influence of a kinematic hardening model on cold strip levelling simulations in terms of resulting roll reaction force, final strip flatness and strip shape within the rolls. Only the work of Madej et al. [16] that investigated hot levelling at 650 °C and of Müller et al. [2] that considered industrial levelling processes at temperatures ranging from 850 to 1000 °C and discussed the influence of hardening model at 850 and 900 °C deal with hot levelling of plate. As the heavy plate levelling of structural steels is performed at temperatures as high as 1000 °C, the aim of the current study is to investigate the importance of kinematic hardening in the hot heavy plate levelling process at the upper temperature limit of 1000 °C with help of simulations. Since the cyclic material behaviour of S355 at 1000 °C is currently unknown, the current work also puts forward a high temperature uniaxial and cyclic material characterization scheme and calibration of Chaboche kinematic hardening model as well as its implementation in a hot heavy plate levelling simulation. Based on a simulation study of plates with varying degree of flatness deviations, the suitability of isotropic and kinematic hardening models are systematically compared with regards to process parameter layout, evolution of the plate geometry during levelling and final plate geometry.

Materials and Methods

Material characterization. The current study investigates the hot levelling of previously hot-rolled and cooled 10 mm thick S355 structural steel heavy plates at 1000 °C. Isothermal uniaxial tension and cyclic characterization of the plate material provided by AG der Dillinger Hüttenwerke is performed using the TA Instruments Dilatometer DIL805T with inductive heating capability. Cylindrical test specimens with a gauge diameter of 4 mm and a gauge length of 7 mm as shown in Fig. 3a are taken from the plate in rolling direction. Planar anisotropy is not investigated since the hot heavy plates of the investigated thickness are usually isotropic.

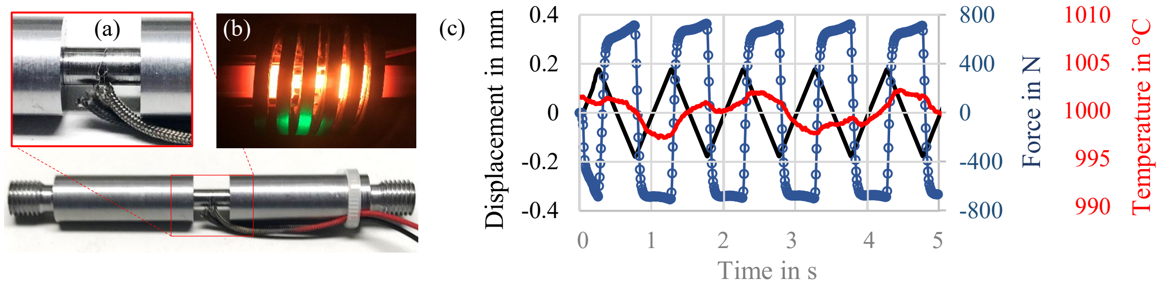

Fig. 3 (a) Specimen used for material characterization (b) hot characterization at 1000 °C and (c) cyclic test data

The specimens are inductively heated to 1000 °C at a rate of 10 °C/s. The temperature is continuously monitored and controlled with the help of a thermocouple spot-welded onto the specimen in the deformation zone as highlighted in Fig. 3a. The relevant strain rate for testing is taken from the levelling process: The plates usually traverse a load triangle (distance between two consecutive upper rolls) in one second. Moreover, their thickness and neutral fibre length do not change, resulting in only small deformations with maximum strains of ±2.5%. This results in an accumulated maximum strain of 10% per load triangle which corresponds to a maximum strain rate of 0.1 s^{-1}. In this study, viscous effects are neglected and the characterisation is done at a single strain rate to reduce the experimental effort. Consequently, the cyclic tension-compression tests are performed at a constant strain rate of 0.1 s^{-1} and in a strain range of ±2.5% under near isothermal conditions (1000 ± 3 °C), whereas the uniaxial tension tests are performed until a maximum strain of 5% at the same constant strain rate. Three repetitions are performed and the averaged data is used for inverse modelling. The cyclic displacement paths and resulting force are shown in the Fig. 3c and it can be seen that the data does not change significantly with the number of cycles.

Determination of material model parameters via inverse FE modelling. Based on the force-displacement data obtained from tensile and cyclic characterization, the elastic, isotropic and kinematic hardening material models are calibrated. A standard inverse modelling technique shown in Fig. 4 is employed, where the experiment is replicated in a purely mechanical isothermal FE simulation at 1000 °C (cf. Fig. 3b) by applying the corresponding tool displacement with respect to time. The difference between the squared sum of experimental and simulated forces for the applied displacement is minimized using the Nelder-Mead algorithm by varying the material model parameters. The material models and the determined parameters follow.

Elasticity model. The elastic component of the stress strain curves is modelled according to Hooke's law and the elasticity modulus is determined to be approximately 29 GPa for the investigated scenario. This value is used in all simulations in this study.

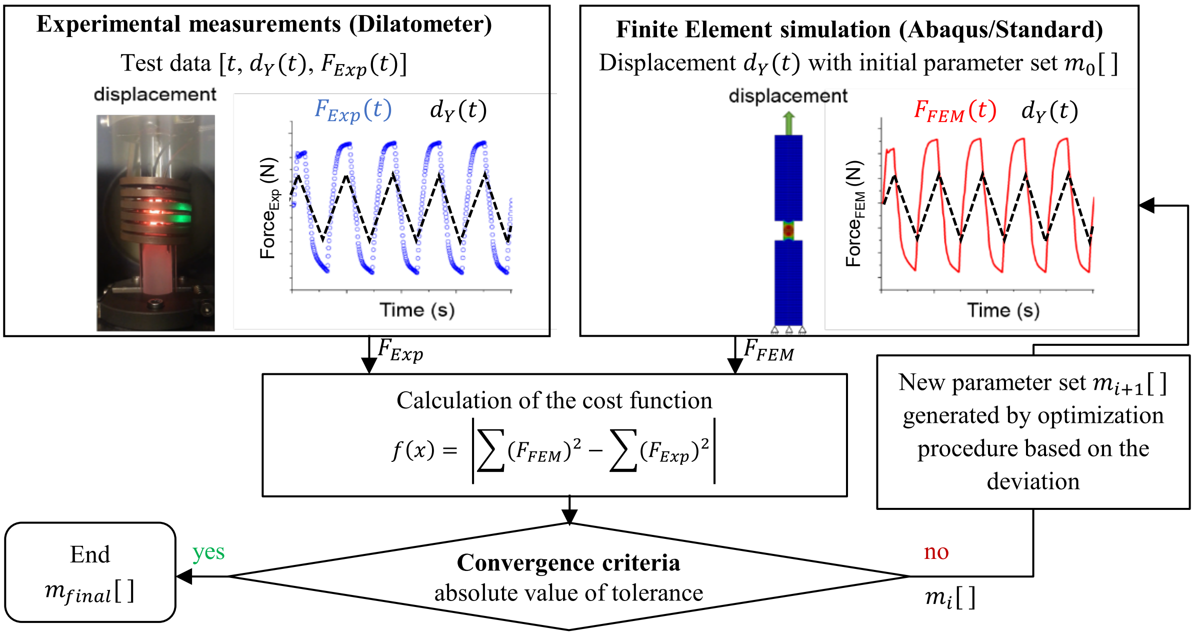

Fig. 4 Inverse modelling method used to determine the material model parameters

Isotropic hardening material model. The isotropic hardening model is derived based on the monotonic material response via uniaxial tension tests. For isotropic hardening, the exponential hardening law according to Voce [17] is used, where the yield stress σ^0 is a function of equivalent plastic strain ε^P. In Eq. 1, σ_0 is the initial yield strength (identified via the 0.2% strain offset method), Q_∞ is the hardening parameter and b is the nonlinearity parameter. These three parameters are determined based on the inverse modelling technique. The resulting stress-strain curve is illustrated in Fig. 5a along with the experimental measurements. It can be seen that the Voce law can model the stress-strain behaviour of the material quite well for the investigated strain range. The strains occurring in the current levelling processes are generally lower than 5%. The determined material parameters are shown in Fig. 5a.

$$\sigma^0 = \sigma_0 + Q_\infty(1 - e^{-b\varepsilon^P}) \quad (1)$$

Kinematic hardening material model. In this study, the experimental cyclic data does not change significantly with the number of cycles for the investigated strain range (cf. Fig. 3c). Therefore, only the kinematic component of the nonlinear combined hardening law according to Chaboche-Lemaitre [10] available in Abaqus/Standard is sufficient to model the cyclic data. The kinematic hardening component of this model is formulated in Eq. 2 and Eq. 3. The evolution of yield stress is described using a back-stress tensor α, which is a function of plastic strain.

$$\sigma^0 = \sigma_0 + \alpha(\varepsilon^{Pl}, \varepsilon^P) \quad (2)$$

The differential increment of the back-stress tensor, formulated in Eq. 3, depends on both the plastic strain range ε^{Pl} and the equivalent or accumulated plastic strain ε^P.

$$\dot{\alpha} = C\frac{1}{\sigma^0}(\sigma - \alpha)\dot{\varepsilon}^{Pl} - \gamma\alpha\dot{\varepsilon}^P \quad (3)$$

In this formulation, C and γ values depend on the amount of kinematic hardening and nonlinearity. The experimental and predicted cyclic stress-strain data is shown in Fig. 5b. It can be seen that the magnitude of the yield stress in the backward load cycle σ_B is much lower than the corresponding forward yield stress σ_F, which means that the material exhibits kinematic hardening at this temperature and strain rate. The corresponding material model parameters are also given in Fig. 5b. The initial yield strength of the material at this temperature and strain rate is 49 MPa, which is same as that of the isotropic hardening model.

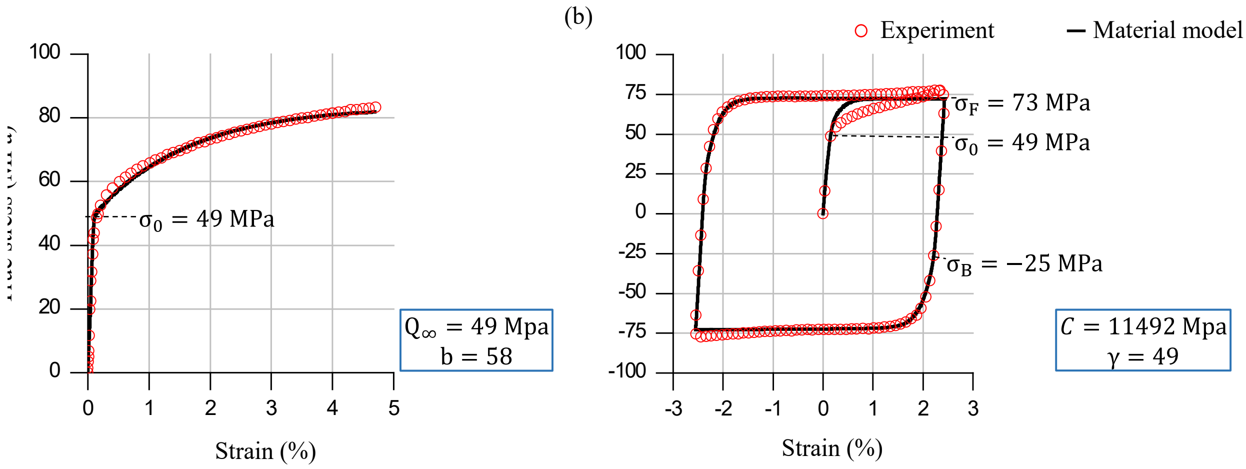

Fig. 5 Stress-strain curves determined via (a) uniaxial tensile testing and corresponding isotropic hardening model and (b) cyclic testing and corresponding purely kinematic hardening model

FE model setup and simulations of heavy plate levelling. In this study, an implicit dynamic simulation of a typical nine roll heavy plate leveller with five fixed lower rolls and four movable upper rolls is performed using Abaqus/Standard. The vertical positions of the upper rolls can be adjusted according to the flatness deviation of the incoming plate and the required plastification (fraction of plate thickness undergoing plastic deformation) the plate has to undergo to eliminate these defects. This study is limited to plates with 2D windable flatness deviations. Therefore, plane strain conditions are assumed and the 2D plate is meshed with eight-node plane strain biquadratic elements with reduced integration (CPE8R) in Abaqus/Standard as shown in Fig. 6. Based on a mesh convergence analysis, eight elements over the plate thickness, each with a size of 1.25 mm×1.25 mm are used for discretization. The rolls are modelled as 2D rigid bodies. The interactions between the rolls and the plate are defined using the Coulomb model with a friction coefficient of 0.2.

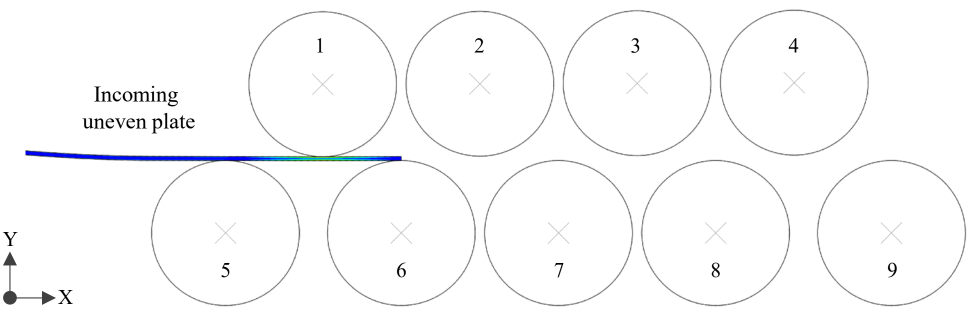

Fig. 6 2D model of the levelling setup

The previously determined material model parameters are assigned to the plate using the corresponding in-built isotropic and kinematic hardening material models in Abaqus/Standard. The levelling process simulations are carried out in two stages. In the first stage, the roll positions for the upper rolls are determined using the controlled levelling model developed in [3] based on isotropic hardening behaviour. This controlled model gives the roll positions that impose a specific amount of plastification and result in a nearly flat plate. The roll setup used in the current study always ensures a minimum plastification of 40% at roll 1. In the second stage, levelling of the defective plates is simulated with the previously determined isotropic and kinematic hardening models separately. The upper rolls first translate vertically according to the positions identified in the first stage and then start rotating and thus push the plate through the leveller. Finally, the results obtained in the second simulation stage with the two different material models are analysed and compared.

Geometry of the heavy plates. In general, the higher the flatness deviation, the larger the local plastic deformation the plate has to undergo during levelling. To evaluate if the different material models induce differences in material behaviour that are amplified by the magnitude of the initial flatness deviation, three different plates with varying magnitude of 2D windable flatness deviations are investigated. The plate geometries are modelled using standard sinusoidal waves with identical wavelength but varying amplitude. The dimensions of the waves are designed based on the commonly occurring 2D windable flatness defects after hot-rolling and cooling of 10 mm thick S355 heavy plates at AG der Dillinger Hüttenwerke. In the end, three plates of thickness 10 mm, total length of around 5000 mm, a fixed defect wavelength of 1800 mm and varying defect heights of 15, 50 and 100 mm as shown in Fig. 7a are modelled.

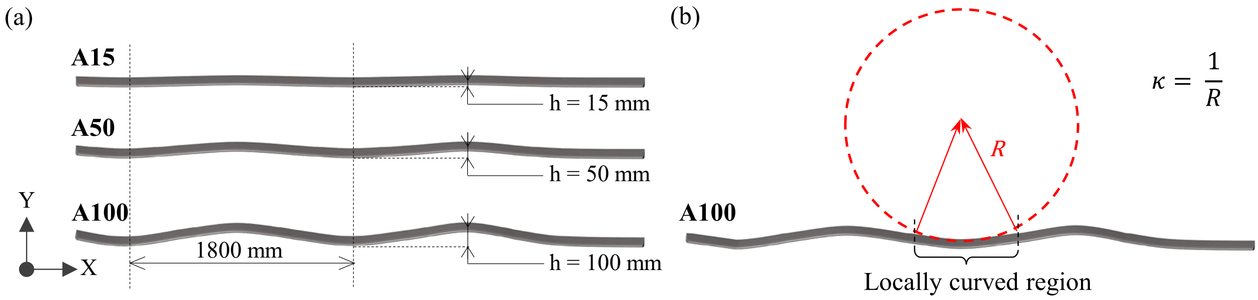

Fig. 7 (a) 2D models of the plates with windable flatness deviations of varying magnitude and (b) schematic of calculation of the local curvature κ by fitting the defect of the plate to a circle

Determination of local curvature. After the simulation, the shape of the plate and the roll reaction force experienced by the rolls can be obtained directly. The magnitude of the flatness deviation is quantified using the local curvature 'κ', which is the inverse of the radius of the approximate circle R that fits the defective zone of the plate [3]. Since the plates studied in the current process are composed of waves of similar length and height, the local curvature of only the central wave as shown in Fig. 7b is calculated. A schematic of the procedure to determine the local curvature is also illustrated in Fig. 7b. Using the coordinates of the neutral fibre of the plate, its local curvature before and after the levelling process is determined.

Results and Discussion

Based on the difference between the output variables of simulations using isotropic and kinematic hardening models, the relevance of considering kinematic hardening in levelling simulations is assessed. Firstly, the local strain imposed on the plates is studied to see if the range of the stress-strain curves obtained experimentally is sufficient for the simulation. After that, the reaction force experienced by the levelling rolls and the shape of the plate during the levelling process are discussed. Finally, the resulting flatness of the plate after levelling is studied.

Verification of strains and plastification. Simulation results show that the plates A15, A50, A100 undergo maximum plastic strains of ±0.052%, ±0.178%, ±0.389% with isotropic hardening and ±0.048%, ±0.171%, ±0.371% using the kinematic hardening models, respectively. This implies that the plates undergo very small local deformations far below the material characterization limits of ±2.5%. Moreover, the maximum plastic strain is always observed at the plate surface while the neutral fibre is not deformed. As mentioned above, the levelling setup ensures a minimum plastification of 40% in case of a flat plate but when defective plates pass through the rolls, the actual plastification is way higher. i.e., the plates A15, A50, A100 undergo a plastification of 72%, 90%, 95% based on isotropic hardening and 70%, 89%, 94% based on kinematic hardening models in the first load triangle at roll 1, respectively. Thus, the isotropic hardening model generally predicted slightly higher strains and plate plastification compared to the kinematic hardening model.

Maximum roll reaction force during levelling. The maximum specific reaction force (force per unit width of the plate) of the upper rolls during the levelling process for the different initial plate geometries and the two material models is plotted in Fig. 8. It can be seen that for a particular plate geometry, kinematic hardening always results in a lower amount of maximum roll reaction force compared to the isotropic hardening. This can be explained by the lower yield stress of the material upon load reversal when kinematic hardening is considered.

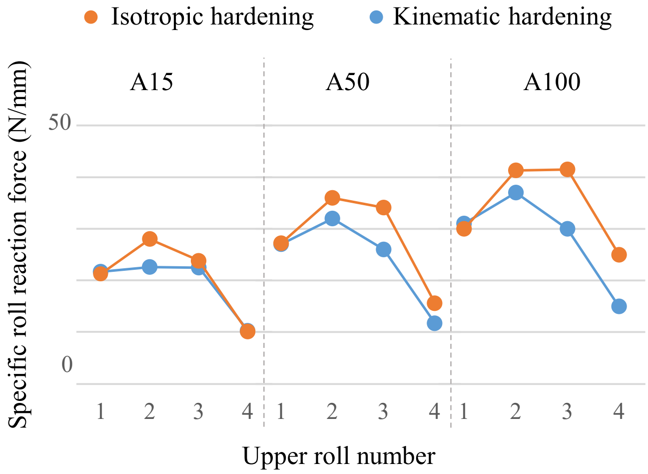

Fig. 8 Maximum specific reaction force experienced by the upper levelling rolls according to the simulations with different material models

In all these cases, the difference in reaction force of roll number 1 is the lowest as the plate just starts undergoing plastification and the loading here is unidirectional. The difference gradually increases with further rolls in case of A50 and A100 whereas in case of A15 the difference increases at roll number 2 and later decreases. This inconsistent trend is probably due to complex interactions of material properties and plate geometry. The plate A100 requires the highest maximum roll reaction force and also yields the greatest difference between the reaction forces.

Plate shape during levelling. As the plate passes through the leveller, it undergoes alternating bending operation. To understand how the plates behaviour under this bending load is influenced by different material models, the shape of the plate in between the rolls of the leveller during the levelling process is shown in Fig. 9. It can be seen that, for the same roll setup, the shape of the plate deviates for the isotropic and kinematic hardening models.

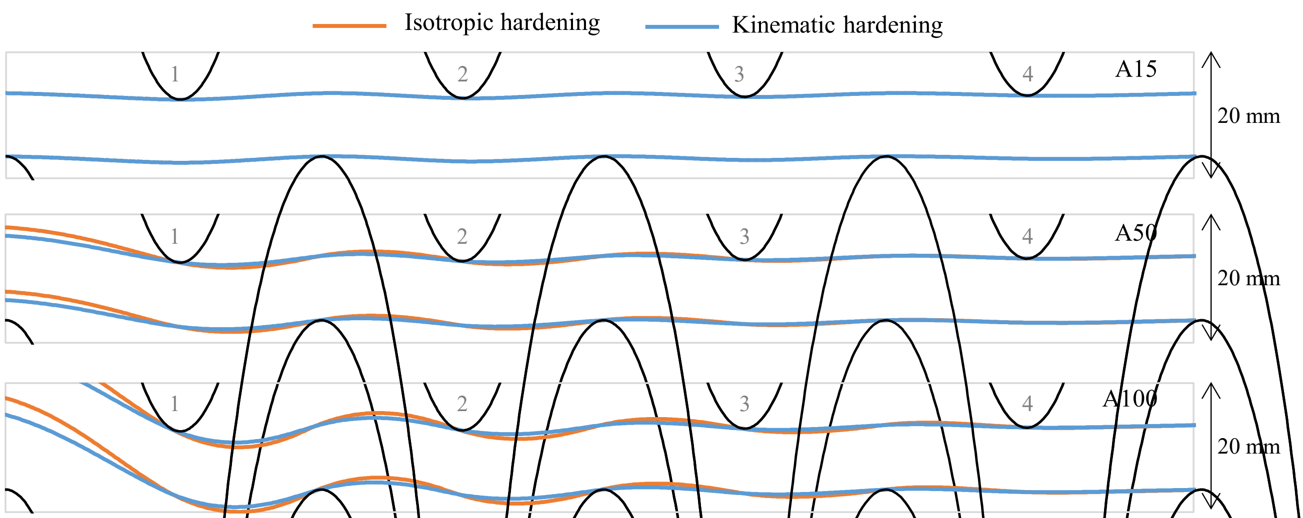

Fig. 9 Shapes of the heavy plates as they pass through the leveller rolls according to simulations with different material models

This is most noticeable, at the first and second levelling rolls, where the plate undergoes plastic deformation. This is due to the difference in yield stress predicted by the used material models. In addition, this difference is highest for the plate A100 with the highest magnitude of initial flatness deviation as this plate undergoes the highest amount of plastification to eliminate the defects, thereby resulting in a higher plastic strain. Thus, the extent of increase in yield stress caused by the isotropic hardening model is much higher for A100 than for A15.

Plate shape after levelling. The shapes of the investigated plates after levelling with isotropic and kinematic hardening models are depicted in the Fig. 10.

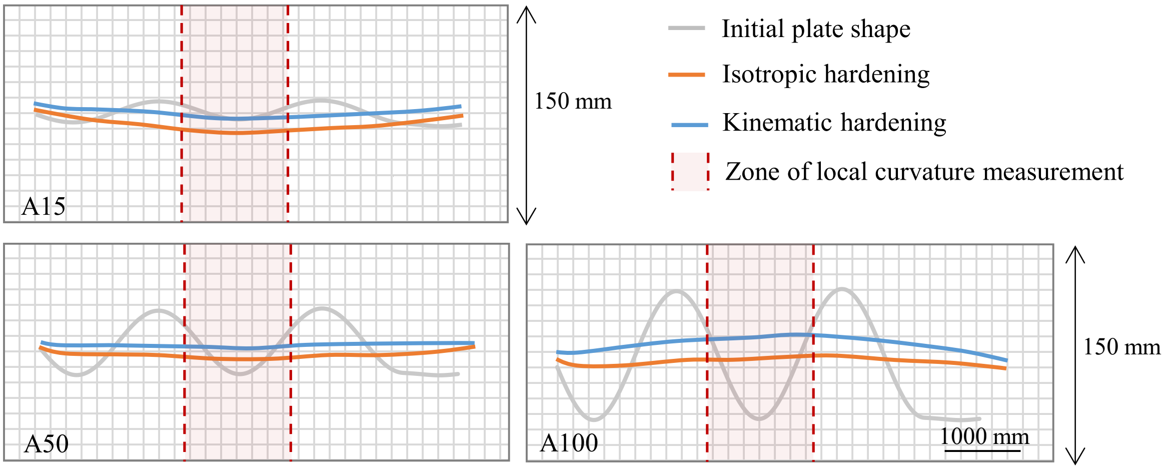

Fig. 10 Initial and final plate shapes obtained from simulations with different material models

After the levelling process, the flatness deviations are significantly lower compared to the initially defective plates. Also, the visual shapes of the levelled plates in the Fig. 10 are not significantly different when different material models are used. For a quantitative analysis, the residual local curvature of the plates in the central zone depicted above is evaluated and discussed below.

Residual local curvature of the plate after levelling. According to DIN EN 10029, for a structural steel heavy plate section (length < 4000 mm; width 600 – 1999 mm), the final flatness is acceptable if the curvature is below a threshold of 20×10^{-3} m^{-1}. The local curvature before and after levelling is analysed for all plates within the zone shown in Fig. 10. As shown in Fig. 11, before levelling, the local curvature of the initial plates increases from A15 to A100 as intended by the design of the flatness deviations discussed above. In case of the plates A50 and A100, the initial curvature is beyond the aforementioned threshold represented by the horizontal dashed line in Fig. 11.

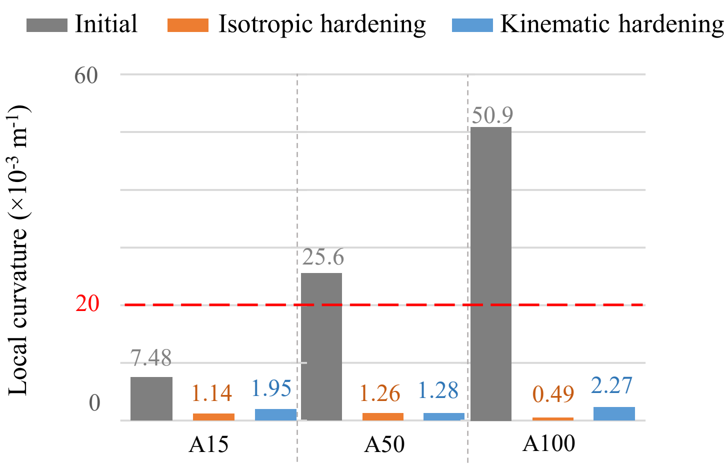

Fig. 11 Local curvature parameter for the studied plates initially and after levelling with different material models

After levelling, the flatness deviation and consequently the local curvature within the plates is significantly reduced in all cases. The results therefore indicate that every simulation irrespective of the consideration of kinematic hardening predict a local curvature that is far below the threshold curvature. The plates still exhibit some residual curvature after levelling as seen in the Fig. 11. The absolute values of the residual local curvature are only slightly different when different material models are used. Nevertheless, for the plate A100, the local curvature is reduced by a factor of 100 for the isotropic and 22 for the kinematic hardening model. In contrast, for the plate A50, it is reduced by a factor of 20 for both material models. Finally, for the plate A15, its initially low local curvature is further brought down by a factor of 6 and 4 with isotropic and kinematic hardening models, respectively. In all these cases, a slightly higher residual curvature is exhibited by the kinematic hardening model compared to the isotropic hardening model. This is due to the slightly lower plastification of the plate and also due to the fact that the roll setup is determined by the controlled levelling model that uses an isotropic hardening model.

Discussion of the results. A higher roll reaction force and a lower local curvature of the plate are evident when the isotropic hardening material model is used. The plate undergoes progressive deformation while moving through the roller leveller and therefore higher accumulated plastic strains occur in the plate towards the leveller outlet. This leads to a higher plate yield stress in case of the isotropic hardening model. When a kinematic hardening model is used instead, the yield stress lowers for every load reversal during alternate bending and thus, the overall yield stress is relatively lower. Moreover, the influence of the hardening model on the roll reaction force is more pronounced in case of a highly defective plate as this plate locally undergoes a higher degree of plastic deformation during the levelling process. In the future it might be worthwhile to investigate if material rate sensitivity and cyclic viscoplasticity additionally influence the force prediction for highly defective plates.

Furthermore, the study of the plate shape during the levelling process also shows a noticeable influence of the hardening model. A similar trend as in the roll reaction forces is observed. i. e., the influence is more prominent for higher magnitudes of flatness defects. However, final plate geometry and corresponding residual local curvature of the levelled plates reveal that an acceptable flatness is achieved irrespective of the hardening model. From the analysis of the roll reaction force and the plate shape, the importance of hardening model from the point of view of hot levelling process design can be evaluated. It can be inferred that the kinematic hardening is significant for both the roll forces and the mid-process plate shape. However, from the perspective of the resulting geometry of the plate, both isotropic and kinematic hardening models resulted in an almost flat plate with identical values of residual local curvature irrespective of the magnitude of initial flatness deviations within the plate.

Summary and Conclusion

In this study, the importance of considering the kinematic hardening in FE simulation of hot heavy plate levelling process of S355 steel at 1000 °C was investigated. Voce isotropic hardening and Chaboche kinematic hardening models were calibrated based on isothermal uniaxial and cyclic material characterization and later implemented into hot heavy plate levelling process simulations separately. Upon comparing the results, the following conclusions can be drawn.

- From the perspective of reaction forces experienced by the rolls, a kinematic hardening model resulted in up to 40% lower reaction forces in extreme cases compared to an isotropic hardening model. Therefore, for designing a levelling setup based on the roll reaction force or torque, considering the kinematic hardening of plate material yields more realistic prediction. This is especially useful for exploiting machine limits in process layout.
- From the perspective of the plate shape and its residual local curvature after levelling, the influence of the material model is minimal. For the investigated cases, a maximum local curvature difference of 11% is recorded when kinematic hardening is considered and the obtained local curvature after levelling is acceptable in all cases irrespective of the used material model. Thus, for determination of leveller roll positions to eliminate the flatness defects, an isotropic hardening model is sufficient.

While highly desirable, the experimental validation of the levelling results shown in this study is challenging. On the one hand, due to difficulty in generating plates with precisely known initial geometry and on the other hand, due to challenges in extracting the required output variables precisely from an industrial hot leveller that elastically flexes during levelling operations.

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