Simulation of Hot Plate Rolling using LS-DYNA©

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1 Abstract

Creating a virtual model of a hot plate rolling process involves many challenges. In an attempt to address these, a research project called FINBEAM ("Full Scale Integrated Workability Modelling") was initiated by Jernkontoret and the Swedish steel industry, financed by the Swedish innovation agency, VINNOVA. The purpose was to bring research institutes, industry and software developers together to reach a common modeling ground for simulation based design of hot working processes for the steel industry in Sweden. A proper description of the material behavior is of outmost importance and a material modelling approach was initiated where the material behavior at high temperatures, strains and strain rates is described. At these temperatures, the material will recover between the rolling passes which demands a stress relaxation model to be added as well. The material test basis for calibrating the data for the material model is the Gleeble test and a test scheme was carried out with various deformation rates and temperatures. During hot plate rolling, the material experiences very high deformations which puts demands on the Finite Element model. The way to remedy this was to use a result mapping approach between each roll pass. To accommodate this, LS-OPT© was used as a simulation driver for transferring the result between passes, starting simulations and extracting results. This paper will present the theory behind the material model and the simulation modeling approach together with numerical results compared with physical hot plate rolling passes.

2 Introduction

Hot plate rolling is indeed a thermo- mechanical process where the thickness of a hot metal strip is reduced in several steps, see Fig. 1. The name hot plate rolling indicates that the temperature is above the recrystallization temperatures meaning that the material will recover between the different roll passes.

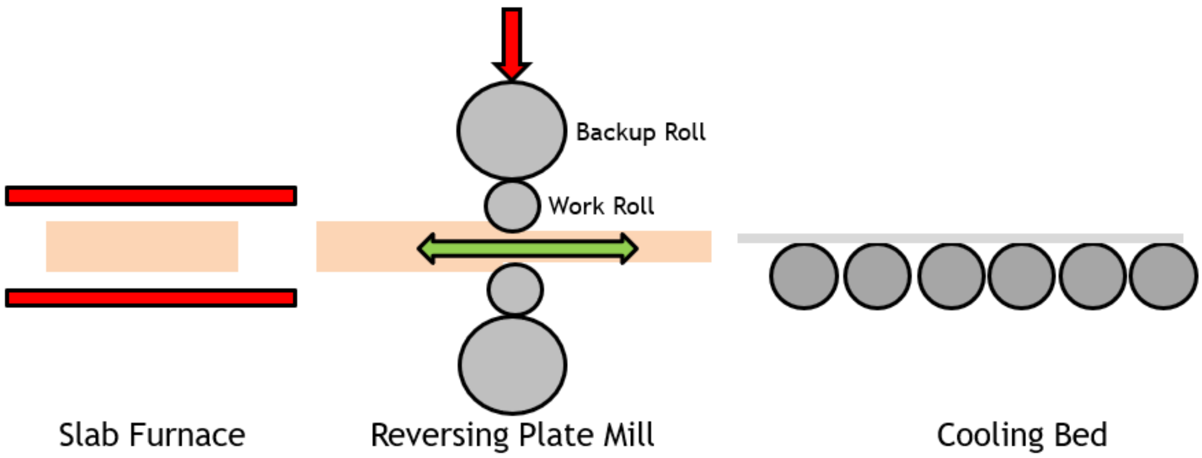

Fig. 1: Schematic layout of a hot plate rolling mill

Although this process is widely used, the modelling attempts are often done using empirical or semi empirical models. One of the reasons for this is probably the wide range of physical processes that occurs during a hot plate rolling process and the huge difference in focus size of these processes. On a macroscopic level, the hot plate rolling mill is a gigantic unit capable of producing several thousands of tonnes in rolling force on a plate which has a temperature of more than thousand degrees centigrade. On a more intermediate level, the thickness of the hot plate is reduced from a 220 or 290 mm plate down to 4-174 mm plates in the SSAB Oxelösund Plate Mill resulting in very high plastic deformation at high strain rates and temperatures. Focusing on a microscopic level, the material will experience stress recovery, relaxation, and grain growth. To consolidate the research and modelling efforts on these subjects, a research project called FINBEAM ("Full Scale Integrated Workability Modelling") was initiated by Jernkontoret and the Swedish steel industry, financed by the Swedish innovation agency, VINNOVA. The aim is to bridge the gaps between the different research areas but also promote the use of modelling in the different focus areas.

3 Simulation of hot plate rolling

Simulation of hot plate rolling has many challenges that must be addressed when developing a simulation methodology. Firstly, hot working often involves very high deformations and hot plate rolling is certainly not an exception. These deformations cause mesh distortion which could cause accuracy issues or element inversion especially in later roll passes. There are several ways to remedy this, where meshless methods (EFG), arbitrary lagrangian eulerian formulation (ALE) or 3D adaptivity with mapping of results are examples of these methods.

As the plate is reduced in thickness it will increase in length by the same ratio. For the later passes, the plate will be several meters long which of course result in a very large simulation time. Fortunately, the thermal and mechanical solution will become steady state so there is a possibility to solve this by modeling a section of the blank. This requires an overall solution control that keeps track on the position of the submodel on the full plate geometry and compensates the simulation times for the actual process times.

One of the major challenges when doing hot working simulations is to describe the material behavior. The model must be capable of describing how the material behaves for large strains, strain rates and high temperatures. In addition to that, at these high temperatures, the material will anneal which results in stress recovery as the stresses are reduced with time in the plate which of course will affect the material behavior in the subsequent roll passes. On a microscopic level, the deformations will cause increase in dislocation density due to the work hardening and sub grain growth. When choosing a suitable material model, it is necessary to determine a proper level of detail. If the level of detail is too low, its usability will be limited since it will not capture the process specifics nor the changes in process setup. On the other hand, it will be easy to calibrate, set up and require short simulation times. The opposite is true if the model detail is too high. This would result in a model that is expensive and time consuming, both to calibrate using experiments and run in a simulation. In the FINBEAM project, a material model approach was chosen that could handle the strain, strain rate and temperature influence on the stress. To accurately model time and temperature influence on the level of stress, a stress recovery model was added as well.

When modelling hot plate rolling, both mechanical and thermal boundary conditions are necessary. Quantifying these could be a cumbersome task due to the high temperatures, sizes and the very high forces involved. When determining the boundary condition coefficients, it is therefore often necessary to rely on inverse methods and probabilistic assumptions. Also, the physical measurements are often done in a production type of environment which is not necessarily tailored for these types of deterministic studies.

4 Material modelling

The material model used in this work is implemented as a user defined material model in LS-DYNA© and it contains the following specifics, work hardening, dynamic softening, static recovery, and static recrystallization.

Work hardening The work hardening model is based on the interplay between storage and annihilation of dislocations described by the Estrin and Mecking model [1].

$$\sigma_{EM} = \sqrt{\sigma_s^2 - (\sigma_s^2 - \sigma_0^2)\exp\left(-2B\bar{\varepsilon}_p\right)} \quad (1)$$

where σ_s is the saturation stress (peak stress), σ_0 is the initial yield stress, *B* is a material parameter and $\bar{\varepsilon}_p$ is the effective plastic strain, see Fig. 2 (first half).

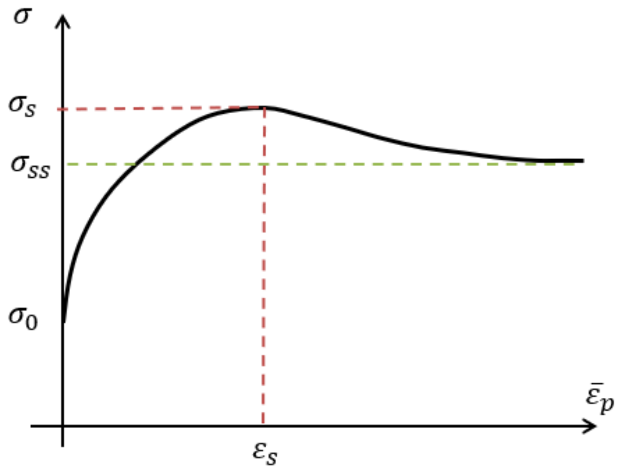

Fig. 2: Description of workhardening and dynamic softening

The stresses can be related to deformation temperature and strain rate through the Zener Hollomon parameter *Z*

$$Z = \max\left(\dot{\bar{\varepsilon}}_p, \dot{\bar{\varepsilon}}_p^{min}\right) \exp\left(\frac{Q_{def}}{RT}\right) \quad (2)$$

and the general form

$$\sigma_i = a_i \ln(Z) + b_i \quad (3)$$

where $\dot{\bar{\varepsilon}}_p$ is the effective plastic strain rate, $\dot{\bar{\varepsilon}}_p^{min}$ is the minimum strain rate for which the parameter fit is done to prevent unphysical values of σ_i, Q_{def} is the activation energy, *R* is the gas constant and *T* is the temperature. In Eqn. (3), a_i and b_i are constants determined from material testing.

The material model is implemented using a hypo- elastoplastic formulation and the isotropic von Mises yield criteria. Using a mixed kinematic isotropic-kinematic hardening with mixing factor $\beta \in [0,1]$ the yield stress becomes

$$\sigma_y = \sigma_0 + (1-\beta)H\bar{\varepsilon}_p \quad (4)$$

where *H* is the material hardening.

Dynamic Softening The effect of softening due to dynamic recrystallization is included in the prediction of the flow stress. This is done by introducing the parameter *X* as suggested by Hodgson et al. [2], which is the fraction which is dynamically softened beyond a saturation strain ε_s, see Fig. 2 (second half).

$$X = \frac{\sigma_{EM} - \sigma}{\sigma_s - \sigma_{ss}} \quad (5)$$

where σ_{ss} is the steady state stress. The softening is presumed to obey a JMAK equation. transformed into the strain domain.

$$X = \begin{cases} 0, & \bar{\varepsilon}_p < \varepsilon_s \\ 1 - \exp\left(-a\left(\bar{\varepsilon}_p - \varepsilon_s\right)^b\right), & \bar{\varepsilon}_p \geq \varepsilon_s \end{cases} \quad (6)$$

The transient flow stress is predicted using a mixture law between the steady state stress and the Estrin Mecking stress

$$\sigma = \sigma_{EM} - X(\sigma_s - \sigma_{ss}) \quad (7)$$

and the resulting hardening then becomes

$$H\left(T,\bar{\varepsilon}_p,\dot{\bar{\varepsilon}}_p\right) = (1 - X)\sqrt{\sigma_s^2 - (\sigma_s^2 - \sigma_0^2)\exp\left(-2B\bar{\varepsilon}_p\right)} + X\sigma_{ss} \qquad (8)$$

where the strain rate and temperature dependencies for σ_0, σ_s, σ_s, σ_{ss} and ε_s are described using the general form according to Eqn. (3).

Static Recovery After deformation, the material softens due to static recovery and static recrystallization. The recrystallization description follows the by e.g. Zurob et al.[3]. The static recovery stress, σ_{nrx}, is modeled by

$$\sigma_{nrx} = \sigma_0 + \Delta\sigma \qquad (9)$$

where σ_0 is the initial yield stress and $\Delta\sigma$ is the change in stress due to dislocation climb given by

$$\frac{d\Delta\sigma}{dt} = -\frac{64\Delta\sigma^2}{9M^3\alpha^2E(T)}\nu_D \exp\left(-\frac{U_0}{RT}\right)\sinh\left(\frac{\Delta\sigma\nu b^3}{kT}\right) \qquad (10)$$

where M, α, υ_D, b are physical constants related to the properties of the FCC iron lattice, U_0 is the activation energy for climb, υ is the interaction volume, $E(T)$ is the Young's modulus, T is the temperature, and R and k are the universal gas constant and Boltzmann constant respectively.

Static Recrystallization It is assumed that the softening is caused by the recrystallized grain growth by annihilating deformed structure with high dislocation density and by this replacing it with new grains with a low dislocation density and constant stress σ_0. The recrystallized fraction is described by the static recrystallization factor X_{nrx} which is described via a standard JMAK expression

$$X_{nrx} = 1 - exp\left(-0.693\left(\frac{t - t_{start}}{t_{50}}\right)\right) \quad (11)$$

where t is the total time, t_{start} is the start time of the recovery and t_{50} is the time required to reach 50 % recrystallization.

Finally, the combined recovery stress state is expressed by a law of mixtures using Eqns. 9 and 11

$$\sigma_r = X_{nrx}\sigma_0 + (1 - X_{nrx})\sigma_{nrx} \qquad (12)$$

5 Material calibration

Producing material data with Gleeble The parameters for describing the work hardening, dynamic softening, static recovery, and recrystallization are determined through Gleeble tests at elevated temperatures ranging from 850 to 1250 deg C and strain rates ranging from 0.1 to 30 1/s. The single-hit tests were made using Gleeble 3800 (Hydrawedge) thermomechanical simulator. The Gleeble test is performed by compressing a cylinder with radius 5 mm and height 15 mm at a constant strain rate and temperature to a prescribed compression strain and then holding the strain allowing for the material to recover. The compression force, strain and temperature of the specimen is continuously monitored. The testing procedure, and its evaluation, is in greater detail described in Pyykkönen et al. [4].

Evaluation of material parameters The three characteristic stresses (yield, saturation stress, and steady-state stress) and the strain at the position of the saturation stress, as shown in Fig. 2, are fitted to the experimental data based on Eqn. (3). This requires 8 parameters plus the activation energy given in the Zener expression in Eqn. (2). These parameters are optimized simultaneously with linear optimization methods, and the common activation energy in the Zener expression gives reliable expressions to extrapolate as well, if needed.

The work-hardening behavior and parameter *B* as given in Eqn. (1), is fitted to the initial part of the compression curves after yielding. A single parameter is needed to model the hardening response for all tested conditions with various temperatures and strain-rates.

Dynamic recrystallisation is evaluated for those few cases whereas the steady-state stress is lower than the saturation stress. This typically occurs for lower strain-rates like 0.1 1/s. Parameters in Eqn. (6), *a* and *b*, are fitted to the evolution in stress after saturation to steady-state. Since higher strain-rates are typically seen in hot-rolling, dynamic recrystallisation will be of less influence.

Finally, after the single-hit with Gleeble the rate of relaxation is measured with the Gleeble. The loss in strength is related to both dislocation assisted recovery (Eqn. 10), and static recrystallisation (Eqn. 11). The dislocation recovery is the most important part and will start directly. The time dependent loss in stress measured by the Gleeble is fitted to Eqn. 10, simultaneously for all tested cases in order to derive one activation energy for recovery and one activation volume. Static recrystallisation requires nucleation of new grains, and their growth, and will be of importance at later stages of softening. It is also a quantity that is of interest to follow for material developers to capture the refining of the material. In this work the t50 expression in Eqn. 11 is fitted to Gleeble data, which was coupled with laser induced ultrasonics (LUS) in order to detect grain-size changes in-situ at testing. The method of testing and its evaluation is described by Malmström et al. [5].

Fig. 3 presents the correlation of a compression test at various temperatures at a strain rate of 1 1/s. The effect of dynamic softening is clearly visible in the stress strain response. The response of simulated compression and hold Gleeble tests is presented in Fig. 4 for temperatures 1050 and 1150 degC and a strain rate of 1 1/s.

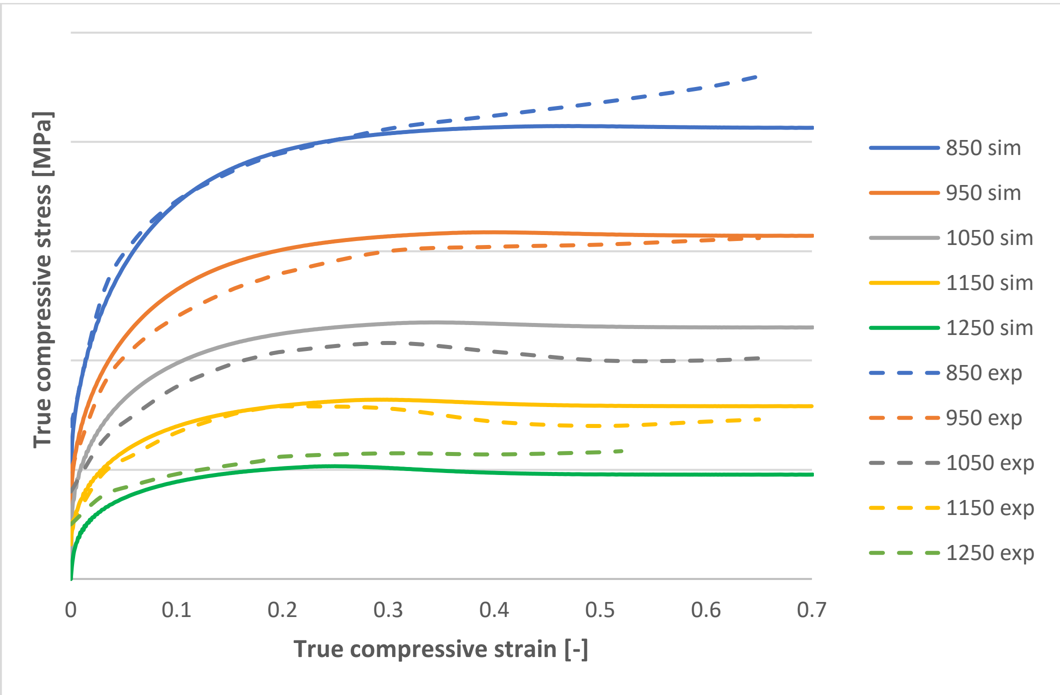

Fig. 3 Experimental (dashed) and predicted (solid) hardening curves at 1 1/s strainrate

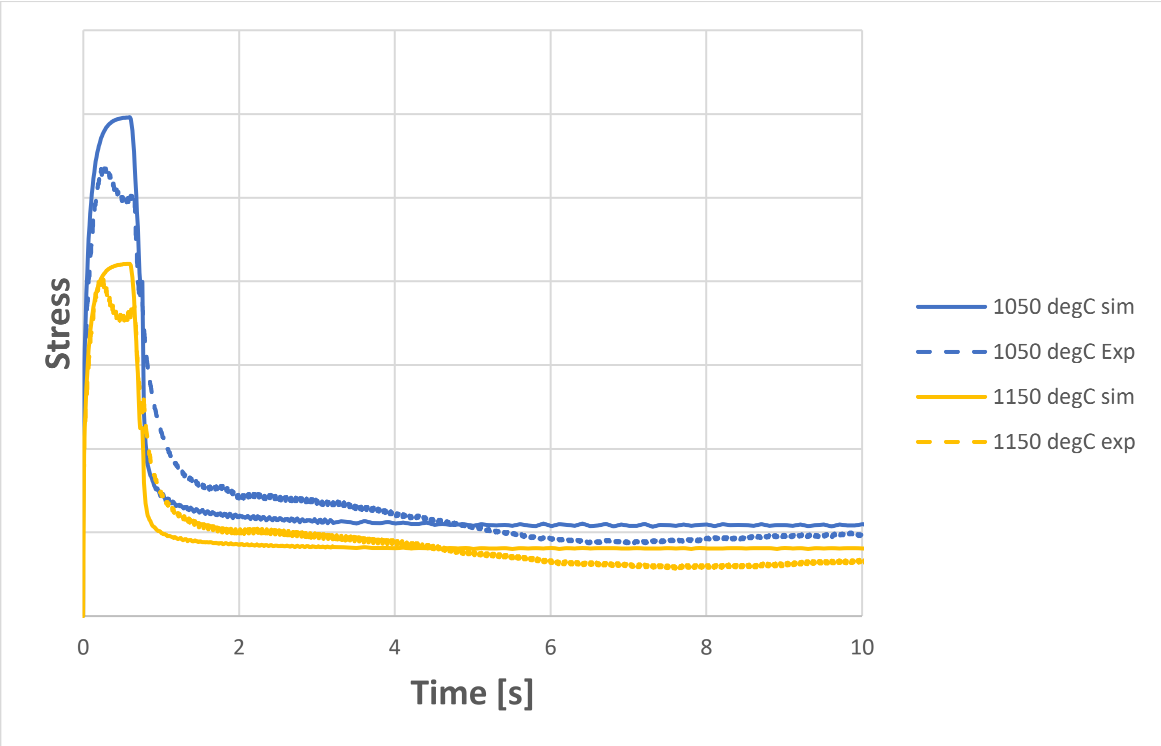

Fig. 4 Experimental (dashed) and simulated (solid) response from a compression at 1 1/s strainrate and holding Gleeble test

6 Hot plate rolling process model

As an initial attempt to model the hot plate rolling process, it is assumed that the plate rolling process follows plane strain conditions. Thus, it can be modeled using one row of elements with displacement constraints in the width direction. In future work, the proposed methodology can be extended to full 3D to study e.g. edge effects. During hot plate rolling, the model will experience severe mesh distortion, see Fig. 5. The approach to remedy this in the present work is to use mapping between the different roll passes. The mapping is done using LS-PREPOST© which has capabilities to map stresses, strains and history variables between solid element meshes.

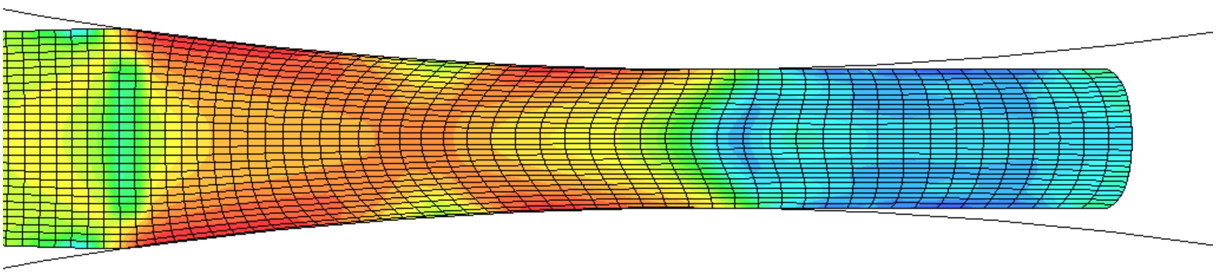

Fig. 5: Mesh distorsion in a hot plate rolling simulation

Another issue that must be solved is the fact that since the hot plate length increases each pass, the simulation termination time will increase accordingly. Fortunately, since this work aims at predicting the overall response of the rolling process, it is possible to utilize the fact that both the thermal and mechanical response quickly reaches a steady state, see Fig. 6. Thus, it is only necessary to simulate a smaller portion of the rolled plate. Therefore, as the solution is mapped to a new mesh, it is at the same time mapped to a pre- defined length keeping the simulation time at a minimum.

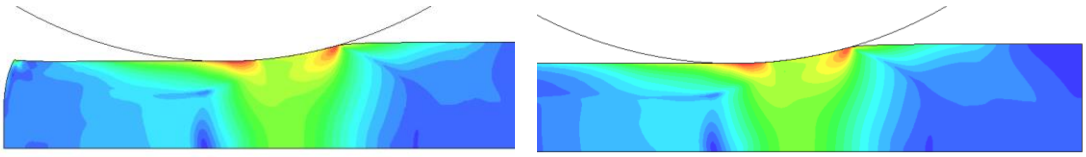

Fig. 6: Von Mises stress at the beginning (left) and end (right) of a 1 m plate rolling showing the steady stress state from the contact between the rigid work rolls (upper) and the deformed work piece (bottom)

The rolling part of the simulation is suitable for the explicit solver due to that the rolling speed is relatively fast, several meters per second, especially in combination with the fact that the model will only represent a smaller part of the rolled plate. However, past the work rolls, the hot plate will cool due to radiation and convection to the surroundings. As the plate increases in length for each roll pass, this will increase the cooling time of the plate which can be several seconds. Since this step, in the reversing passes of the Plate Mill involves pause with no deformation, it is tempting to decrease the simulation time by increasing the mass scaling for the cooling part.

Based on the challenges and the corresponding solutions above and the aim of the current work, a roll, cool and map methodology is implemented, see Fig. 7. The basis of the methodology is a parameterized model where the input is the reduction and rolling velocity for each roll pass. Together with the initial length of the plate it is possible to keep track of the current length, height before each roll pass and the relative position of the point of interest. Also, with this information it is also possible to calculate the cooling times between the rolling passes. Based on this information, a complete simulation scheme can be set up using python scripting.

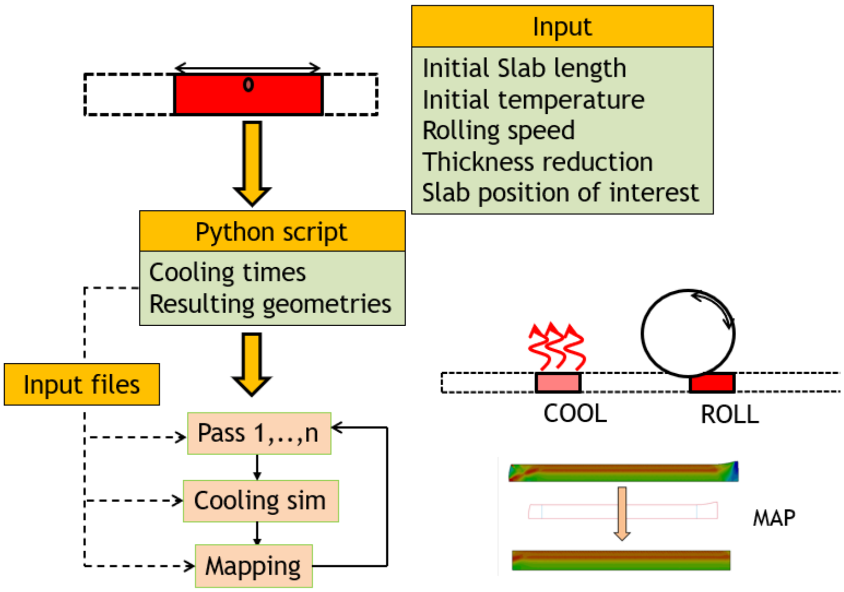

Fig. 7: Roll, cool and map methodology

To keep track of the process and run each step and script in consecutive order, LS-OPT© is used. The benefits of using LS-OPT© as a process flow tool are several. Firstly, the flow chart setup in LS-OPT© makes it easy to set up or modify a process simulation using the parameterized input. Also, any file that needs to be moved from one process step to the next is easily defined with a folder structure. If the need for optimization or a parametric study arises, it is trivial to change the parameters to be part of a Design of Experiment. Lastly, responses can be extracted automatically from each stage which gives the user an overview of the results without having to manually post- process each process stage.

The explicit mechanical solver in LS-DYNA© is used coupled together with the implicit thermal solver for all simulations. The thermal boundary conditions are radiation and convection to air and heat conductance to the rollers through contact. The work rolls are during hot plate rolling assumed to be rigid, and thick thermal elements are used with a quadratic temperature distribution through the thickness to allow for the surface of the rollers to heat up.

7 Results

The presented material model and methodology is applied on a reversing hot plate rolling process. The plate is in this case reduced from 213 mm to 15 mm in 8 rolling steps. The process data are taken from a production plate rolling process, and it includes the reduction and rolling velocity in each process step. The force is measured and recorded as a mean force during each roll pass. The total process time from where the plate enters the rollers is about 60 seconds.

The process starts when the re-heated hot plate leaves the furnace. Here, it is assumed that the temperature in the plate is uniform. Between the furnace and the rolling mill, the top surface of the plate will start to cool down. Also, descaling operations are done by high pressure water spray after the furnaces and in some passes of the Plate Mill that also will affect the thermal history. The actual temperature distribution of the plate as it enters the plate mill then must be calculated in a preceding step where the plate is allowed to cool down by radiation and convection. The effect of the descaling is not included in this work. As a results from the hot plate rolling simulation, the temperatures are compared against the SSAB Oxelösund Plate Mill process data which are estimated at the mid- section of the plate. Temperature data is also available for the surface of the plate. It is continuously recorded by an IR camera mounted at the exit of the mill. Since the plate is reversing this means that on an odd pass number the measurement is taken after the roll pass before the roll pass for even pass numbers.

Fig. 8 shows the measured and simulated temperatures in the middle of the plate and on the plate surface. The LS-DYNA© simulated and measured mean forces in the SSAB Oxelösund Plate Mill are presented in Fig. 9.

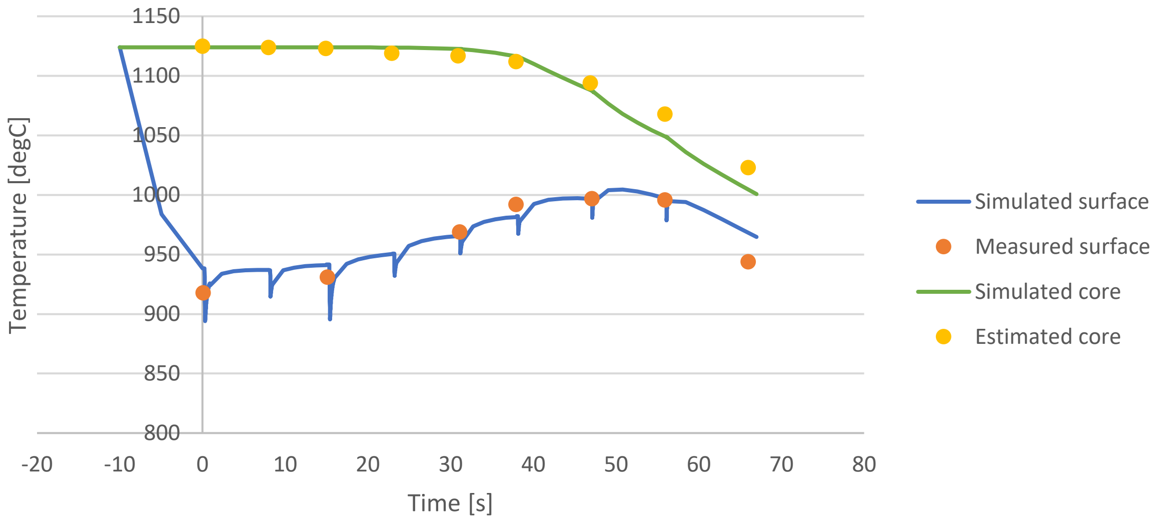

Fig. 8: LS-Dyna simulated temperatures of the hot plate, compared to measured process temperatures for the hot plate core and surface in SSAB Oxelösund Plate Mill

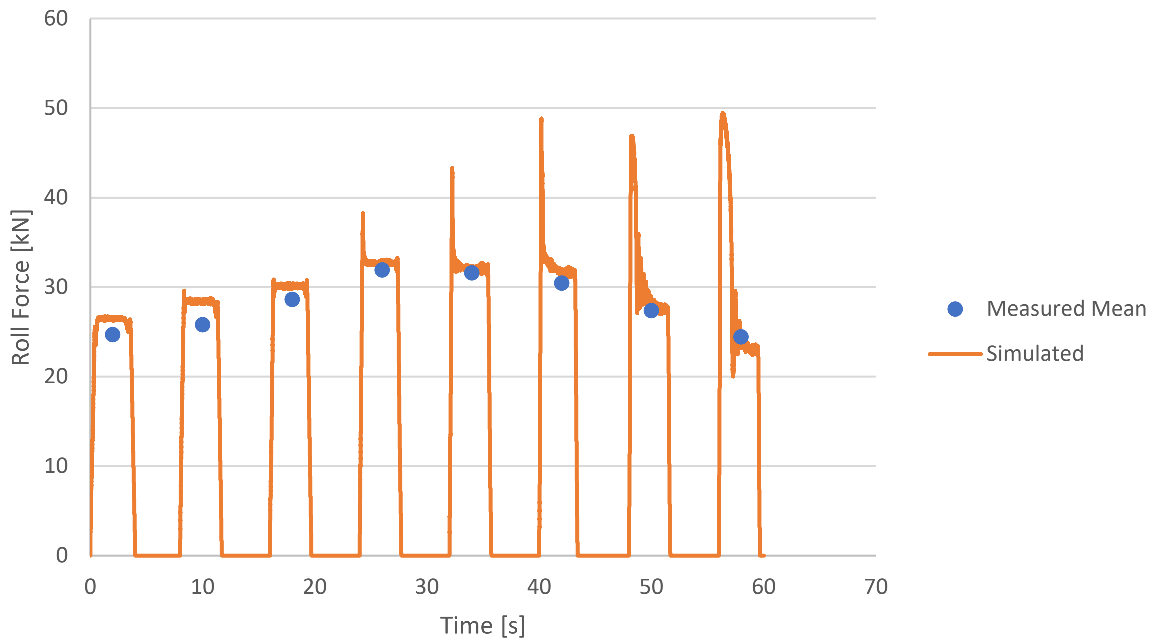

Fig. 9: LS-Dyna simulated roll forces, compared to measured roll forces in SSAB Oxelösund Plate Mill, during hot plate rolling

8 Summary

The aim of this work is to simulate the hot plate rolling process. The approach is not to describe the material mechanisms and microstructure evolution in detail. Instead, a phenomenological approach is made. Based on the results, these types of simulations can serve as a basis for qualitative studies and investigating the effect of process parameters. If more detailed study is required, these simulations can be used to output strain, temperature and material histories that can be used as input in more advanced micromechanical models.

The constitutive description plays a crucial role in this work. It needs to describe the work hardening during a hot plate rolling process which subjects the material to large plastic strains, high strain rates and temperatures. At these elevated temperatures, the material can show dynamic softening which was described using a saturation stress. The temperature and strain rate dependency are modeled using a Zener Hollomon parameter. Due to the high temperatures, the material will recover between the roll passes which is also included in the material model. The work hardening and stress relaxation parameters are determined using Gleeble tests at various strain rates and temperatures. The tests include a holding time at constant strain and temperature to allow for the material to recover.

The modeling challenges when simulating hot plate rolling is mesh distortion and long simulation times. These issues are solved using a roll, cool and map methodology where the rolling and cooling simulations are run as coupled simulations in consecutive order and the resulting stresses, strains, material histories and temperatures are mapped to a novel mesh. LS-OPT© is used as a process flow tool which aids the setup, parameterization, and execution of the hot plate rolling process simulations in consecutive order.

The material model and simulation methodology were used to simulate the hot plate rolling process. In this exemplified case, the plate was reduced from 213 mm to 15 mm in 8 rolling steps where the LS-DYNA© simulated temperatures of the surface and mid- section of the plate as well as the roll forces are in very good agreement with real process data from the SSAB Oxelösund Plate Mill.

9 References

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