Transport of heat and material properties in continuous casting of steel

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Abstract. Liquid steel solidifies within a containment of a continuous casting machine and moves in axial direction as the solidified shell is withdrawn towards the end of the machine. A mechanical model for computing the deformation of the solidifying steel in the roll containment is developed based on the beam theory and on a ferro-static pressure load. The material properties of the steel at high temperatures result from high temperature constitutive equations including creep for the solidified shell between the rolls. The temperature distribution within the solidified shell is computed based on the thermal boundary conditions as in the secondary cooling zone water is spread onto the surface of the steel shell and heat is removed. The solidified steel shell thickness increases along the machine containment up to the point of total solidification. A suitable discretization of the region by the finite beam elements is used to get a suitable mechanical model. The ferro-static pressure acts inside of the solidified shell and causes some bulging of the shell between the roll containment. As there is a slow axial motion of the solidifying shell the numerical modeling of the transport e.g. of heat and of the creep strain, which is computed in each time step, has to be as accurate as possible as a lot of time steps are necessary. Different numerical strategies have been analysed with respect to the accuracy of the computation results.

1. Introduction

A scheme of the continuous casting machine for the production of solidified steel slabs is shown in Fig. 1. The liquid steel is stored within a ladle which is positioned on a ladle turret. From there the liquid steel flows into a tundish and further into the mould. In the mould the first solidification starts as an intense cooling is performed by copper plates which define the cross section of the final cast slab. The solidifying steel shell is withdrawn with a predefined speed. A certain solidified shell thickness is required when the shell moves out of the mould and enters the roll containment. After the mould a defined water cooling is acting on the surface to further maintain the cooling of the steel depending on its grade. In the inside a ferro-static pressure acts on the shell with very high temperature and the distance of the rolls in the roll containment has to be small enough to prevent excessive bending or bulging between the rolls. At these high temperatures steel shows a dominant creep deformation which can be influenced by an appropriate water spray cooling, see [1]. The position of total solidification of the cast slab has to be within the machine containment. After the end of the roll containment the slab is cut at a defined length.
Figure 1. Scheme of a continuous casting machine.

Usually the continuous casting process is operated at constant speed but if some interruptions or planned modifications occur a transient production phase starts which usually is a critical situation for the production of a high quality product. In these transient phase the heat transfer, the bulging of the steel in the roll containment, the withdrawing forces show an interaction which influences the quality of the product and also the level of the liquid steel in the mould. Typically when the ladle, the grade or the tundish is changed, the withdrawal speed or casting speed has to be reduced to a minimum. The increase of the casting speed after such a transient period involves some metallurgical requirements and has to be performed carefully. When increasing the casting speed at a given position the solidified shell thickness gets smaller and bulging is increased at this position. As increased bulging results in inner cracks and reduced quality this is a second criteria which limits the casting speed. Due to some varying parameters, like variations in the shell thickness at high casting speeds, bulging varies with time and hence the level of the liquid steel shows a certain fluctuation which has to be kept small. As a consequence due to disturbances the casting speed has to be adjusted for the best and efficient production. An accurate simulation model of the casting process is necessary to compute these correlations and to get some additional knowledge for an improved production.

2. Mechanical model
A mechanical model of the deformation of the solidifying steel in the roll containment is based on the beam theory. In Fig. 2 the solidifying steel shell and the roll containment is drawn schematically. From the rectangular cross section of the slab a slice is cut out at in the middle of the width in longitudinal direction which is shown in Fig. 3. For a high ratio of width to
thickness of the slab this beam model is a good assumption and represents the deformation of the solidifying shell. The beam has an increasing thickness and is moving with the casting speed in axial direction. In order to keep the effort for the computation reasonable it is assumed that the temperature in the solidifying slab can be computed and there is no coupling considered with the deformation state. The mechanical model of an axially moving beam with defined boundary conditions for the heat transfer on the surface can be solved as a generalized Stefan problem, see [2], considering the axial transport of heat with the moving material. The temperature distribution in the solidified shell in the steady state case only depends on the position $X$ and is independent from the deformation, see Fig. 4. The heat transfer is computed in a separate preceding step considering the flow of heat on the surface with the given boundary conditions and the transport of heat in longitudinal direction. The computation of the temperature is done using a discretized volume model of the beam. With a finite difference method the solution is computed applying an algorithm chosen in the next section and the resulting typical temperature distribution of the solidified shell is shown in Fig. 4. $\zeta$ is the transversal direction in shell
thickness and $X$ is the longitudinal direction along the machine starting at the end of the mould. A suitable discretisation is done in longitudinal and transversal direction using grid and integration points. When reducing the temperature in the steel according to the iron-carbon-diagram at high temperatures it is totally liquid above the liquidus temperature and totally solid below the solidus temperature and between these two temperatures there is a mushy zone where fluid and solidified crystals are present. The solidified shell thickness is shown in Fig. 5. As the material properties of the steel are temperature dependent, the line for $\zeta_0$ shows the position of the neutral axis of the strand beam model.

The basic equations for an axially moving beam with transversal load considering creep deformations are given in [3], where also a method for the computation of $\varepsilon^{cr}$ is proposed. The expression for the mechanical stress in the beam cross-section is

$$\sigma_{XX} = E(T) \left( -Z w''(X) - \varepsilon^{cr}(X, Z) - \varepsilon^{th}(X, Z) \right), \quad (1)$$

where $E(T)$ is the temperature dependent modulus of elasticity taken from [4], $w(X)$ is the deformation of the beam in transverse direction, $\varepsilon^{cr}(X, Z)$ is the creep strain and $\varepsilon^{th}(X, Z)$ is the thermal strain as a function of the longitudinal coordinate $X$ and the transversal coordinated $Z$. With the virtual displacement $\delta \varepsilon = -Z \delta w''$ the formulation of the virtual work results to

$$\delta A = - \int_V \sigma_{XX} \delta \varepsilon dV + \int p_z \delta w dX - \sum_{k=1}^{N_k} F_k \delta w(X_k). \quad (2)$$

with the external load $p_z$ and the concentrated elastic restoring forces $F_k$ which represent the elastic roll of the containment. The temperature is assumed to be constant during the virtual deformation $\delta \varepsilon^{th}(X, Z) = 0$. Using Eq. (1) and $dV = dXdA$ the relation for the bending moment caused by the creep strain is

$$M^{cr} = \int_A E Z \varepsilon^{cr} dA. \quad (3)$$

As Ritz approximations have to be used two strategies have been compared. Global shape-functions have been implemented, see [5], and local Ritz approximations have been used for sake of comparison, see [6]. The two kinds of shape functions are arranged in the vector $\textbf{W}$. Inserting $\textbf{W}$ in Eq. (2) gives a force term caused by the creep strain

$$f^{cr} = \int_L M^{cr} \textbf{W}'' dX. \quad (4)$$

With these shape-functions the consistent force of the external load of the ferro-static pressure

$$f^0 = \int_L p_z \textbf{W} dX \quad (5)$$

and the force caused by the spring elements with the total stiffness $k_k$ at $X_k$

$$Q_{k \text{ spring}} = k_k \textbf{W}(X_k) \quad (6)$$

is computed. $k_k$ is the resulting total stiffness coefficient of the $k$-th roll including the stiffness of the bearings. Finally the stiffness matrix results to

$$\textbf{K} = \int E I \textbf{W}'' \left( \textbf{W}'' \right)^T dX. \quad (7)$$
The number of DOF’s defines the size of the system of equations to be solved, \( q \) is the vector of the generalized coordinates or the vector of the nodal degrees of freedom respectively and the system of equations results to

\[
K \ q + Q_{\text{spring}} = f_{\text{cr}} + f^0.
\]  

(8)

An example for a two-span beam and a constitutive relation is described and computed in [7], where global and local shape functions have been compared. In these results the local shape functions showed some computational advantages for the present mechanical model so that local functions have been used for the further simulations.

In Eq. (1) the stress depends on the longitudinal and transversal coordinate of the beam and is computed at the Gauss-points in the X,Z-plane. The integrals over the cross-section and the length are evaluated by Gauss-integration. The creep strain is computed from the constitutive equation of the material

\[
\dot{\varepsilon}^{cr}(X,Z) = C e^{-\frac{Q}{kT}} \left[ \sigma_{XX} - a_\varepsilon(\varepsilon^{cr}, T) \right]^{n}
\]  

(9)

where \( Q \) is the Arrhenius temperature parameter representing the activation energy and further parameters are given as functions of the temperature \( C(T), n_\varepsilon(T), n(T), a_\varepsilon(\varepsilon^{cr}, T) \), see [4] for more details, numerical values and examples. The ordinary differential equation is integrated in the time domain with an implicit Runge-Kutta-Method to get the local creep increment \( \Delta\varepsilon_{\text{cr}}^{cr} \) within the time step. Due to the axial velocity \( v_0 \) the creep strain is transported with the material along the beam axis. The one-dimensional transport equation with homogeneous initial and boundary conditions

\[
\frac{\partial \varepsilon^{cr}}{\partial t} + v_0 \frac{\partial \varepsilon^{cr}}{\partial X} = 0, \quad \varepsilon^{cr}(X = 0) = 0
\]  

(10)

is used to compute the actual values of \( \varepsilon^{cr}_{\text{cr}}(X,Z) \). The Finite-Difference-Method (FDM) is applied to get a system of ODE’s, where the Gauss-points are used for the discretisation. This system of ODE’s again has to be integrated in the time domain to get the convective part of the inelastic strain \( \varepsilon^{cr}_{\text{con}} \). The total creep strain is

\[
\varepsilon^{cr}_{\text{tot}} = \varepsilon^{cr}_{\text{con}} + \Delta\varepsilon^{cr}_{\text{cr}}.
\]  

(11)

When computing the deformation of the beam the modeling of the creep behavior of the steel at high temperatures is important, see [1, 4] and Eq. (9) is used in this contribution. With the converged results for the computed creep strain from Eq. (9) the deformation of the solidified steel shell results and the iterative procedure for the next time step can be started. A lot of time steps are necessary for the simulation of the transport of the shell particles through the whole machine as the particles need about 30 minutes for the considered distance

3. Analysis of the axial motion

As it is very important for the accuracy of the computed results the modeling of the transport in continuous casting of steel is analyzed separately in more detail. Various operation conditions for the axial motion of the shell have to be simulated. Applying \( N \) non-adaptive equidistant grid points, the axial transport is modeled by transferring the field variables of the material after each converged time step. The partial differential equation for the axial transport of a representative field variable \( a(X,t) \) with the axial speed \( v_0 \)

\[
\frac{\partial a(X,t)}{\partial t} + v_0 \frac{\partial a(X,t)}{\partial X} = 0
\]  

(12)
is solved by discretization with $N$ points applying the FDM. The first derivation with respect to the longitudinal coordinate $X$ is computed using the central difference equation

$$\frac{\partial a(X,t)}{\partial X} = \frac{a(X_{i+1},t) - a(X_{i-1},t)}{X_{i+1} - X_{i-1}}.$$  \hspace{1cm} (13)

At the right boundary the left-sided difference equations are used. Instead of the used field variable $a(X,t)$ the temperature or the non-elastic creep strain are used. The non-elastic creep strain $\varepsilon_{cr}(X,t)$ is computed at these points and has to be transported according to the axial motion of the material. After inserting the difference equations for the longitudinal coordinate $X$ into the transport equation a system of $N$ ordinary differential equations results for the field variable in the discretized domain:

$$\dot{a} + B a = 0$$ \hspace{1cm} (14)

An implicit one step Runge-Kutta-method is used for integration where the equation for the $j$-th time step and the $i$-th point at $a_{ij}(X_i,t_j)$ is

$$a_{ij}(X_i,t_j) = a_{i,j-1}(X_i,t_{j-1}) + \Delta t f \left[ t_{j-1} + \theta \Delta t, a_{i0}(X_i,t_0) + \theta \left( a_{ij}(X_i,t_j) - a_{i,j-1}(X_i,t_{j-1}) \right) \right].$$ \hspace{1cm} (15)

Insertion into Eq. (14) results in a system of $N$ equations

$$(I - B \theta \Delta t) a(t_{j+1}) = (I + B \Delta t - B \theta \Delta t) a(t_j),$$ \hspace{1cm} (16)

which can be solved for $a(t_{j+1})$. Different methods have been tested for a typical triangular reference signal. For different discretisations in time and different Runge-Kutta-methods the solution for the test problem is quite different. Slow axial speed of about 1 m/min and a machine length of about 30 m results in a high number of time steps so that diffusion due to the numerical method has to be minimized. Fig. 6 shows the exact and the resulting numerical solution for the chosen method for a triangular test function after a transport of a distance of 1 m. The numerical method and discretisation with the minimal diffusion and the smallest errors has been chosen for the following computations.

Figure 6. Transport of a triangular test function.

Figure 7. Normalized simulation result for the bulging of the shell.
4. Computation results for representative operation conditions

A representative example of steady state bulging of the steel shell in the continuous casting machine is computed applying the best numerical solution method found above. A constant axial velocity of \( v_0 = 1.0 \text{ m/min} \) and the temperature field shown in Fig. 4 is taken, which has been computed as described above. Due to the axial motion there is a steady state condition which means that the deformation does not change with time and \( w(x,t) = w(x) \). Due to the axial speed \( v_0 \) and the creep strain Eq. (10) leads to an asymmetric result for the deformation between two successive rolls, whereas the loading and the mechanical boundary conditions are symmetric. The solution for the bending deformation of the steel shell in the continuous casting machine is given in Fig. 7, where also the elastic deflection of the roll containment with the given stiffness \( k_k \) of the rolls and the bearings can be seen. The elastic deflection of the rolls is increasing as the ferro-static pressure increases with the longitudinal coordinate \( X \). It can be seen that at some positions the bulging deflection is higher. These excessive bulging deformation results from the fact that the distance between two rolls is higher, which comes from design requirements. The computed representative solution for the stress and strain for the nodal points is shown in Fig. 8 and Fig. 9 for a length of ten rolls in the region of the end of the casting bow and as a function of the actual shell thickness. In longitudinal direction the solution looks quite periodic as the roll containment shows a constant distance between the rolls in this region. In transversal thickness direction it can be seen that the stress is higher and the strain is lower for lower temperatures occurring at the surface. The distance of the rolls in the containment dominates also the stress and strain level. A high strain value can be seen at the inside at the front of the solidified steel. Some quality measures can be derived from this solution with the assumption that cracks can be initialized for high strain values.

This model was also used to performing a parametric study for process and design parameters in order to get new insight in the process and the quality of the product. The parametric study has been performed to analyse the influence of the distance of the roll in the containment, the influence of the constitutive creep formulation, the casting speed, the kind of distortion of the shell thickness or the temperature distribution. The convergence has been studied for various parameter configurations. Furthermore this model was used to compute some special operation conditions like transient operation conditions during a change of the tundish or ladle.
Additionally for a certain deviation in the shell thickness at the end of the mould due to non-continuous processes the computation has been performed. In this case some simplifying assumptions for the temperature field are necessary and for different casting speeds the evolution of the shell thickness profile has been computed. This model represents an axially moving beam with axially varying stiffness and the analysis of the results show some new ideas for the modification of the process parameters.

5. Conclusion
A simulation model for the computation of the behaviour of the solidifying steel in a continuous casting machine is developed. A beam model is considered which is in contact with a high number of rolls of the containment. The axial motion of the material through the casting machine is modeled and analysed in detail in order to guarantee an efficient and converged solution. This accurate simulation model involves the computation of the creep of the solidifying steel and is able to consider various operation parameters and evaluates their influence on the machine operation.

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