MODELLING OF SOLIDIFICATION OF CONTINUOUSLY CAST STEEL BILLETS USING FINITE ELEMENT METHOD

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Abstract

This paper presents actual computational possibilities and experiences from the modelling of qualitative parameters of continuously cast steel billets in ProCAST simulation software achieved during a solving of research projects with industrial partners. The ProCAST simulation programme is a part of the equipment of the "Laboratory of modelling of processes in liquid and solid phases" of the "Regional Materials Science and Technology Centre" at the Faculty of Metallurgy and Materials Engineering at the VSB - Technical University of Ostrava. In the paper, the list of the required results is reported and based on own practice, the suitable form of their post-processing is recommended. According to the required results for radial continuous casting of steel billets, the most appropriate way of the definition of the numerical model with a finite element mesh and computation procedure are described. Also, the problems with determination of the thermodynamic properties of materials are discussed.

Keywords: Steel, continuous casting, numerical modelling, porosity, hot tears

1. INTRODUCTION

Continuous casting technology is currently the primary method in production of steel billets. In continuous casting, a ladle is placed over a tundish which feeds one or more moulds beneath through a submerged entry nozzle. The mould area is the zone of primary cooling. Molten steel solidifies and shrinks in the mould, inevitably forming a gas gap which is a restrictive condition in continuous casting, between the solidified shell and the mould's copper wall. The mould design should adapt to the heat shrinkage of the billets, therefore a converse taper is recommended to use for the mould inner cavity to reduce the formed gap, increase the thickness of the solidified shell, and to improve the casting speed and the surface quality of the billets [1, 2, 3]. The steel strand is continuously withdrawn from the mould by the guide and pinch rolls. Immediately below the mould, the strand meets a series of water-mist sprays that help extract a significant portion of heat from the moving strand, thereby completely solidifying the steel. We are talking about the zone of secondary cooling.

The primary and secondary cooling must ensure the continuous casting of steel without strand breakouts and other interruptions with an acceptable level of external and internal defects. The very intensive cooling in the secondary zone, the very high casting speed, the very high casting temperature, the deflection of the guide and pinch rolls, the too big pressure of the pinch rolls, the surface reheating of the billets in the secondary cooling zone can be the source of the internal hot tears or cracks, porosity and segregation [4, 5, 6, 7]. But the internal defects also depend on the steel cleanness that is a function of the conditions of refining of steel during secondary steelmaking and casting [8].

One of the ways how to monitor and optimize the processing parameters of the continuous casting technology and the quality of the semi-finished products is the application of numerical modelling [9], in which numerical methods are used for solving mathematical equations of the mass transfer, movement and energy. Currently, many types of simulation software exist [10] and for users it is very complicated to choose the best one for optimization of specific process. Therefore, the paper presents the actual computational possibilities and experiences of the modelling of the qualitative parameters of the continuously cast steel billets in ProCAST simulation software achieved during the solving of research projects with industrial partners.

2. REQUIRED RESULTS AND THEIR POST-PROCESSING

The process of solidification of continuously cast steel billets relates with kinetics of billet temperature field. Therefore, the numerical modelling of the qualitative parameters (such as thickness of the shell in the end of the mould, the metallurgical length, the centerline porosity, the hot tears and cracks, or segregation) is possible only with knowledge of the temperature field of the billet along the casting strand from the bath level in the mould to the end of the secondary cooling zone. The temperature field is established by solving the Fourier heat conduction equation, including the latent heat release during solidification. The ProCAST simulation program solves the partial differential equations using the finite element method.

As it can be seen from numerical modelling results of paper's authors, in **Figure 1a** the temperature field (T_A, T_B) through the cross section (A) and on the surface (B) of the cast format is usually evaluated. The determination of the thickness of the shell in the end of the mould (ST) and the metallurgical length (C) is better to predict from the Fraction Solid ($FS_{C,ST}$) where the colour scale of temperature is transfer to the colour of the melt and solid phase (grey colour typical for solid steel). For the purpose of results comparison with real plant data (from the pyrometers), the point analysis of temperature is also suitable (see **Figure 1b**).

a)

b)

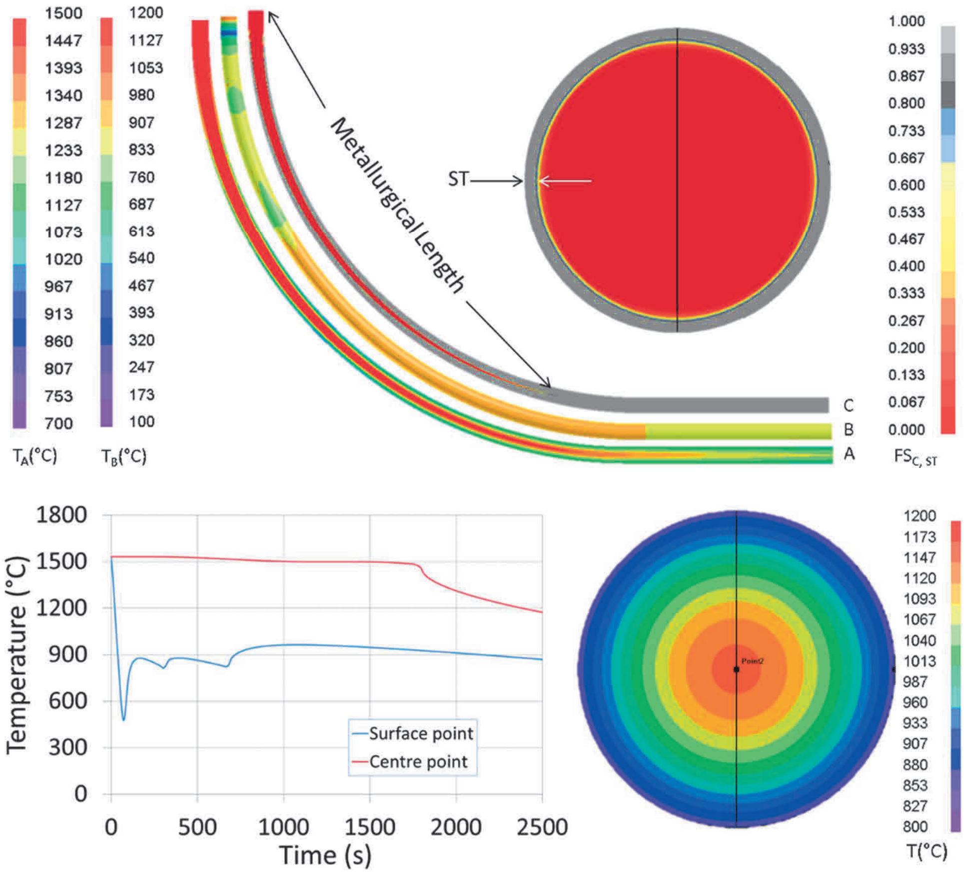

Figure 1 The examples of numerical modelling results

In the case of numerical modelling of continuous casting of steel billets in ProCAST, the range of porosity can be predicted using the Advanced Porosity Module [11]. The Advanced Porosity Module (also called APM) uses the multi-gas approach in order to model gas and shrinkage microporosity, as well as macroporosity and pipe shrinkage. The porosity module is based upon the model developed by Pequet, Gremaud and Rappaz [12, 13]. The porosity is predicted in the positon of the zero pressure of liquid phase in the center of the continuously cast steel billets, as can be seen from the **Figure 2**.

The prediction of hot tears is possible with use of so called Hot Tearing Indicator (HTI) which indicates the depletion of material plasticity above the solidus temperature (see **Figure 3a**), usually in the position just below the mould (starting point of occurring hot tears). The HTI is a "strain-driven" model based upon the total strain which occurs during the solidification. A detailed description of the model of the calculation of the HTI recently derived by Rappaz, Drezet and Gremaud can be found in [14, 15, 16]. The Cracking criterion (see **Figure 3b**) predicts the risk of integrity breaking of the material on/under the surface when the surface temperature of billet is about 400 °C. During the evaluation of the results of the prediction of the risk of the hot tears and cracks, the temperature field with the Cooling Rate and also with the Average Normal Stress is good to give to the mutual context.

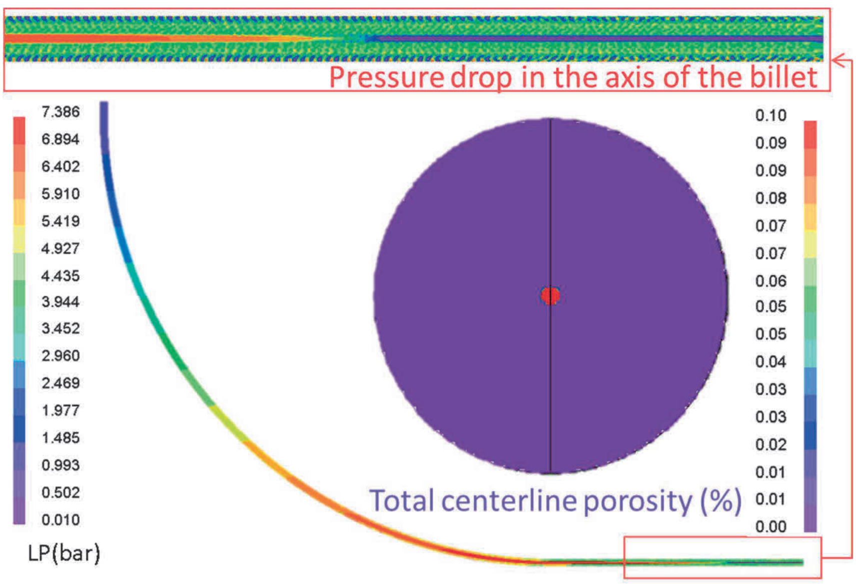

Figure 2 The Liquid Pressure (LP) in the final stage of the local solidification of continuously cast steel billet and the final detected total centerline porosity in the cross section of billet

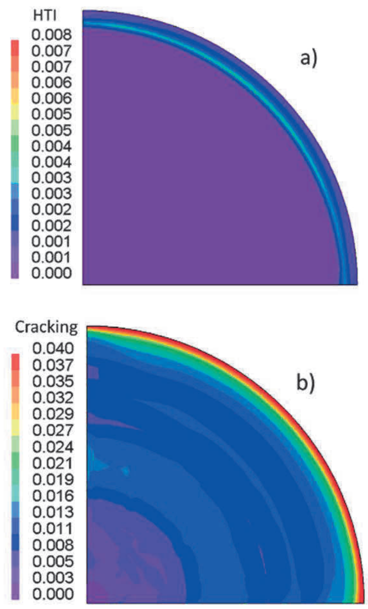

Figure 3 The examples of **a)** Hot Tears Indication (HTI) and **b)** Cracks in steel billet

3. ALGORITHMS OF NUMERICAL MODELLING

During the solving of the research project with the industrial partners, two approaches of numerical modelling with use of finite element method were applied using the ProCAST simulation program: the numerical modelling under Steady State Thermal Conditions and the numerical modelling with Traveling Boundary Conditions. The results of both approaches must be the same although they differ in the preprocessing and processing phase, especially in the preparation of geometry, in the definition of heat transfer during the billet casting, respectively in the computation of the heat transfer with respect of moving of billet through the individual cooling zones. The thermodynamic properties of steel, as well as the boundary and the operational conditions were the same for both types of algorithms.

3.1. Algorithm of Steady State Thermal Conditions of Numerical Model

In the first case, the Steady State Thermal Conditions (SSTC) of computation of defined numerical model was used. The results of SSTC algorithm show the steady state during the continuous casting. Therefore, only the last saved step of computation can be used for evaluation of achieved results.

Under SSTC computation, the geometry of modeled area of radial continuous casting of steel consists of the simplified mould and of the billet which usually represents the entire curved section and also the straight section of the cast strand. In order to simulate the metallurgical length, the geometry must be drawn up to the end of the secondary cooling zone. So according to rough calculation, another approximately 5 m straight section of the strand must be then added to the curve.

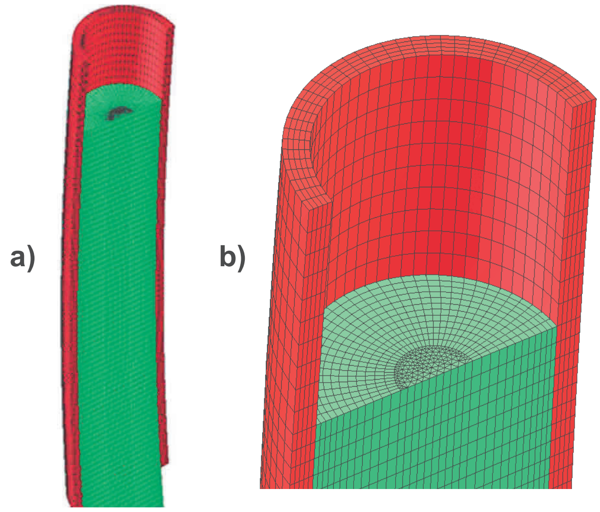

Figure 4 Detail of **(a)** mould geometry with **(b)** computational mesh for SSTC modelling

As it can been seen from **Figure 4a**, the mould geometry can also introduce only the simple tube which is on its inner side in contact with the strand, and on its outer side cooled by water flowing in a closed circuit. The level of steel in the mould can be marked from its upper edge. During the modeling of mould geometry, it is recommended to neglect a converse taper due to the subsequent method of mesh preparation for application of finite element method. If the heat computation is only considered, the submerged entry nozzle can be also neglected. The mesh should be prepared with respect of expected results. For example, if the shell thickness has to be predicted, so the refinement of the mesh near the surface of the billet is good to carry out (see **Figure 4b**). But the use of finer mesh increases the final number of computational elements and therefore also causes the prolongation of computational time. In SSTC computation, the water-cooling in mould is defined by a heat flux boundary condition. Secondary cooling and the rolls are replaced with the thermal boundary condition.

3.2. Algorithm of Traveling Boundary Condition

In the second case, the algorithm of Traveling Boundary Condition (TBC) was used. The computation with use of Traveling Boundary Condition is interesting at first because the results of TBC can be evaluated in each step of computation. The second positive aspect of the TBC is the simplification of the geometry which introduce only the own billet (see **Figure 5**). In the case of stress computation, the next simplification of geometry to the strait billet is necessary. The substantial simplification of computation introduces the use of one symmetrical half of the geometry. The reason for the use of one symmetrical half of the geometry is shorter computational time at a much finer mesh of finite elements. On the other side, the much more effort needs the definition of the heat transfer in primary and secondary cooling zone which are described by User Defined

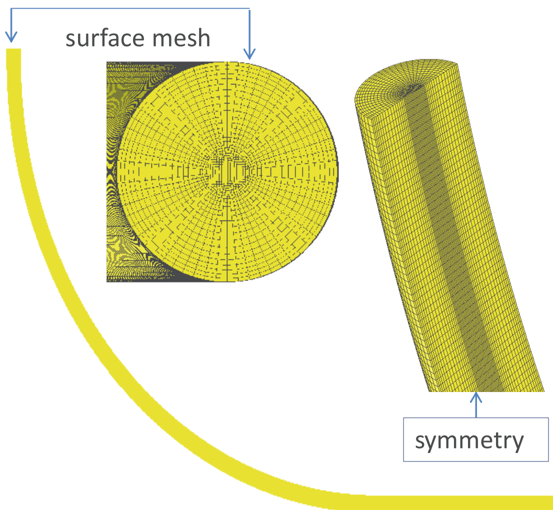

Figure 5 The geometry and computational mesh for TBC modelling

Function in programming language C++. The software offers only the template of User Defined Function, such as heatflux.c and convehtransfer.c. The more details about the definition of heat transfer were published for example in [1, 17].

3.3. Thermophysical properties

In the case of simulating the casting and solidification processes of steel, the following thermodynamic properties depending on the temperature are needed to know: density, enthalpy / heat capacity, conductivity, viscosity. If the prediction of hot tears is also required, the stress properties of steel could be also defined depending on temperature.

Although the methods used for determining the material properties have made a huge advance, it is still very complicated to analyze the values in the area of high temperature, especially concerning the solidus and liquidus temperatures. Also, the identification of these temperatures of phase transformation is still a challenge. Even more complicated it is the case of stress properties specification, which is necessary for predicting the risk of cracks and hot tears. Usually the constant stress values from the forming structure of steel is known, but not from the casting state depending on temperature. In that case the following solution can be applied: experimental methods, empirical equations, Neumann-Kopp rule, thermodynamic database and/or values from the literature [18, 19, 20]. In ProCAST simulation program, the integrated thermodynamic database CompuTherm can be used to calculate all of these thermodynamic properties.

4. CONCLUSION

The paper presented the actual knowledge from the numerical modelling of solidification of continuously cast steel billets including the prediction of qualitative parameters (the temperature field, the metallurgical length, the shell thickness, the porosity, the hot tears and cracks). The overview of required results and their possibilities of visualization and evaluation were listed at the beginning. Then, the two approaches of modelling with finite element method used in ProCAST simulation software were described. It was found that:

- the modelling of solidification of continuously cast steel billet could be solved under Steady State Thermal Conditions, as well as under the Traveling Boundary Condition;
- in both cases, it is useful to apply the condition of symmetry on geometry in order to achieve a shorter calculation time; it is recommended to neglect a converse taper of the billet (in the mould area and also in the secondary cooling zone) due to the subsequent method of mesh preparation for application of finite element method; in the case of modelling with Traveling Boundary Condition, the modeled area introduces only the own billet geometry;
- the quality of the numerical modelling results relates with the accuracy of the thermophysical properties of the calculated steel grades and with the defined conditions of the heat transfer in the primary and secondary cooling zones.

Based on the complex experience, it is possible to confirm that the numerical modelling is a good choice for optimization of the processes, not only the continuous casting of steel. The numerical modelling is appropriate especially under difficult conditions in steel metallurgical plants where it is very complicated and expensive to realize the plant experiments.

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