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STUDY OF SOLIDIFICATION OF CONTINUOUSLY CAST STEEL ROUND BILLETS USING NUMERICAL MODELLING

The paper is dedicated to the verification of solidification of continuously cast round steel billets using numerical modelling based on the finite element method. The aim of numerical modelling is to optimize the production of continuously cast steel billets of round format. The paper describes the pre-processing, processing and post-processing phases of numerical modelling. Also, the problems with determination of the thermodynamic properties of materials and the heat transfer between the individual parts of the casting system, including the definition of the heat losses along the casting strand in the primary and secondary cooling, were discussed. The first results of numerical simulation show the so-called thermal steady state of continuous casting. The temperature field, the metallurgical length and the thickness of the shell at the end of the mould were predicted. The further research will be concentrated on the prediction the risk of the cracks and the porosity based on the different boundary conditions.

Keywords: steel, billet, continuous casting, numerical modelling, metallurgical length

1. Introduction

Continuous casting (CC) technology is currently the main method used to produce the steel billets, blooms or slabs. Molten steel is during CC solidified into „semifinished" products for subsequent rolling in the finishing mills. Enhancement of the number of heats cast in a sequence, if possible without interruption of teeming and without necessary restart, is of utmost significance for increasing the productivity of continuous cast steel. On the other hand, CC of various steel grades requires individual processing parameters. Therefore, a fundamental task of the CC method is the optimization of the processing parameters in order to maximize the safety of the process, to improve the economy and ecology of the technology and mainly to increase the quality of the products [1-5].

To ensure safety of the process, the minimum shell thickness at the end of the mould must be known. When improving the economic and ecological aspects, the maximum casting speed and the minimal superheating of the heat, and also the minimal water consumption is required. The quality of the steel in the continuous casting process directly relates with the temperature changes during the solidification process [6]. The temperature profile must ensure an acceptable level of external and internal defects (i.e. surface depressions/shape defects, depth of oscillation marks, surface and internal cracks, internal porosity, and macrosegregation) [7].

One of the ways how to monitor and optimize the processing parameters of the CC technology, respectively the temperature profile of the cast strand and the quality of the semifinished products is the application of numerical modelling [8-13], in which numerical methods are used for solving mathematical equations of the mass transfer, movement and energy. The advantage of the numerical modelling considering metallurgical conditions of the steel production is the possibility of relatively simple change of the boundary conditions of the CC technology and verification of the influence of these processing parameters changes on the final character of solidification of the casting strand, respectively on the final temperature profile and on the size of the final defects.

Nevertheless, a prerequisite for correct results of numerical modelling is the relevant description of the heat transfer in the steel continuous casting process. Such description is very difficult [14-16], because the cooling and solidification processes of continuously cast products are influenced by many factors [17, 18], such as casting format, casting speed, casting temperature/ superheating, steel grade/ carbon content, erosion of the mould, electromagnetic stirring, efficiency of the cooling in the secondary zone etc.

In this study numerical modelling using the finite element method has been developed for verification of the temperature field, the thickness of the shell at the end of the mould and the metallurgical length for continuous casting of the round steel billets with a diameter of 400 mm. Study is based on investigation of heat transfer behaviour of steel within mould and secondary cooling zone. The heat transfer

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along the casting strand is described by user function defined in the programming language C++. Additionally, the problems with the determination of the thermodynamic properties of materials are discussed.

2. Computational procedure

Generally, the numerical solution of each task is divided into three stages:

1. Pre-processing - it includes the modelling of geometry, process of computational mesh generation and definition of calculation,
2. Processing - it involves the computation in the solver.
3. Post-processing - it focuses on evaluation of the results.

To have a default version of the numerical model of solidification of the steel billets in accordance with real conditions of solidification as accurately as possible, it was important to define correctly the parameters of calculation. The necessary parameters include:

- material properties of steel,
- boundary conditions:
  - casting temperature,
  - casting speed,
  - level of steel in mould,
  - difference of temperature of cooling water between the mould inlet and outlet,
  - heat flux along the mould,
  - heat transfer coefficient along the secondary cooling zone,
  - ambient temperature,
- operating conditions (gravity, ambient pressure),
- criteria of convergence, the so called RUN PARAMETERS or Simulation parameters.

Determination of some boundary, operating and initial conditions is usually relatively not so difficult. The casting speed or the steel casting temperature can be defined according to the real casting conditions. The reliability of the numerical simulation results of the volume defects in continuously cast billets is mainly determined by the quality of the thermodynamic properties of steel and mould material, or by the applied conditions of heat transfer between the individual parts of the casting system and by the method of defining the heat losses along the casting strand. Here, some difficulties can be encountered. First, when steel grade may not be included in the basic material database of the software. Also, the definition of the heat transfer coefficients between the individual components of the casting system is not simple.

2.1. Mathematical formulation of thermal processes and determination of heat parameters

From the physical point of view, the numerical modelling of continuous casting represents the heat and mass transfer under non-stationary conditions where the heat conduction is mainly applied. The other mechanisms of the heat transfer, such as the radiation and convection, play a role mainly at definition of boundary conditions of the process in the secondary and tertiary zone of the CC machine.

Also, the phase changes, which may occur during solidification of the steel, must be included in the numerical formulation. To describe the heat transfer during continuous casting, the Fourier-Kirchhoff equation can be used [19, 20], Eq. (1):

$$\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+v_z\frac{\partial H}{\partial z} \qquad (1)$$

where:

T (x,y,z,t) - the temperature in the coordinate (x, y, z) and in the t time,

H (x, y, z, t) - the enthalpy in the coordinate (x, y, z) and in the t time,

k - the thermal conductivity,

v_z - the casting speed in the z direction.

In the case of radial CC machine, it is good to transform the cylindrical coordinates into the Fourier-Kirchhoff equation Eq. (2):

$$\frac{\partial H}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \phi}\left(k\frac{\partial T}{\partial \phi}\right)+\frac{\partial}{\partial \omega}\left(k\frac{\partial T}{\partial \omega}\right)+v_\phi\frac{1}{r}\frac{\partial H}{r\partial \phi} \qquad (2)$$

where:

r, φ, ω represent the cylindrical coordinates. Equation (2) represents the partial differential equation of the second order and it must be supplemented by equations of the boundary conditions of the 1st, 2nd and 3rd order.

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 the primary cooling. The gaps between the solidified shell and the mould copper wall present a restrictive condition at continuous casting. A scheme of the situation is given in Fig. 1 [21]. The mould design should adapt the heat shrinkage of the billets, therefore it is recommended to use a converse taper for the mould inner cavity in order to reduce the formed gaps, to increase the thickness of the solidified shell, and to improve the casting speed and the surface quality of the billets.

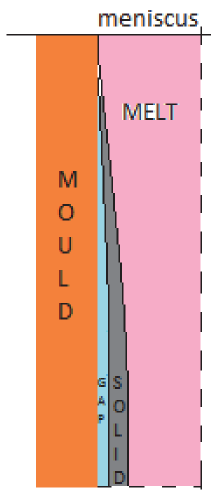


Fig.1. Scheme of vertical continuous casting of steel billet with gap formation

The size of the gap can be determined from the heat balance according to the Eq. (3) [22]:

$$d = \frac{\lambda_g \left(t_p - t_{ko}\right)}{\dfrac{1}{\dfrac{\delta_{Cu}}{\lambda_{Cu}} + \dfrac{1}{\alpha_l}}\left(t_{ko} - t_{H_2O}\right) - AC\left(\dfrac{T_p}{100}\right)^4} \tag{3}$$

where:

λ_g - heat transfer coefficient of the gap gas, t_{H_2O} - temperature of the cooling water,
T_p - the surface temperature,
t_{ko} - temperature of the inner wall of the mould,
δ_{Cu} - thickness of the mould wall,
λ_{Cu} - heat transfer coefficient of cooper,
α_l - heat transfer coefficient between the cooling water and the mould.

The size of the gap influences the density of the heat flux which can be calculated from the Eq. (4) [22]:

$$q = k\left(t_p - t_v\right) \ [\mathrm{W{\cdot}m^{-2}}] \tag{4}$$

where:

k - the heat transfer coefficient [W·m-2·K-1],
t_p - the surface temperature of steel billet on the inner wall of the mould [°C],
t_v - the temperature of the cooling water in the mould [°C].

To calcualte heat transfer coefficient it is possible to use the Eq. (5):

$$k = \left(\frac{1}{\alpha_1} + \frac{s_k}{\lambda_k} + \frac{1}{\alpha_2}\right)^{-1} \ [\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}] \tag{5}$$

where:

α_1, α_2 - the heat transfer coefficient respectively on the inner wall of the mould and from the outer surface of the mould into water [$\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$],
s_k - the thickness of the mould wall [m],
λ_k - the heat transfer coefficient of the copper mould wall [$\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$].

Fig. 2 shows the usual profile of the density of heat flux from the surface of the steel into the mould for the round billets with diameter of 410 mm [24].

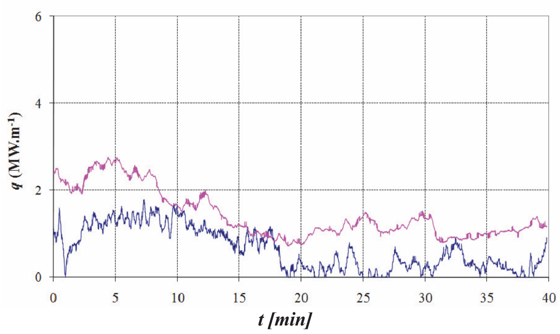


Fig. 2. The example of the profile of heat flux along the mould with diameter of 410 mm cited from lit. source [24]

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 the steel completely solidifying – generally it is the zone of the secondary cooling.

For characterization of the intensity of spraying, the density of the heat flux can be determined from the Eq. (6):

$$q = \alpha\left(t_p - t_v\right) \ [\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}] \tag{6}$$

where:

α is the heat transfer coefficient.

Determination of the heat transfer coefficient during the spraying in the secondary cooling zone is complicated. Usually, the heat transfer coefficients can be specified using the experimental measurement performed on the steel samples of the real continuously cast billets (e.g. [15]). Such measurement uses thermocouples. The cooling performance at measured place (which corresponds to the effect of spraying) is equal to Eq. (7) [23]:

$$P_{i,j} = \frac{U_{i,j}^2}{R_t} - P_z \ [\mathrm{W}] \tag{7}$$

where:

$P_{i,j}$ - the cooling performance at the position i, j,
$U_{i,j}$ - voltage at the measured place i,j [V],
R_t - resistance at the temperature t [Ω],
P_z - heat flux losses [W].

The density of the heat flux at the position of the measured sprayed surface is calculated from Eq. (8):

$$q_{i,j} = \frac{P_{i,j}}{S_s} \ [\mathrm{W{\cdot}m^{-2}}] \tag{8}$$

Where S_s is the surface of the thermocouple. Finally, the value of the heat transfer coefficient can be defined from the Eq. (9):

$$\alpha_{i,j} = \frac{q_{i,j}}{t_s - t_v} \ [\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}] \tag{9}$$

where:

t_s - the average temperature of the thermocouple.

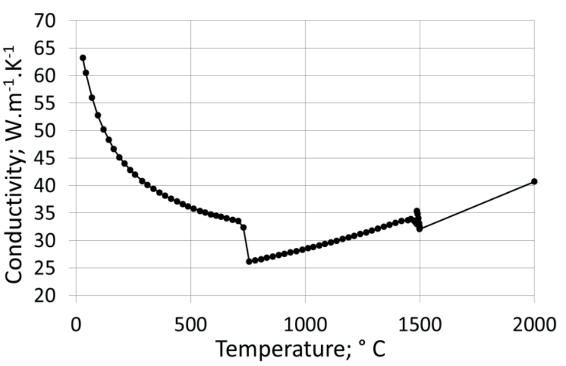
In the presented study, the water cooling in the mould region was described by a user function of a heat flux boundary condition. The user function took also into account the formation of the gas gap between the mould and the steel billets. Also, a different function was used also for definition of the heat transfer coefficients along the casting strand in the secondary cooling zone. Between the individual spray surfaces, the heat loss by conduction and radiation was considered. To be sure of the values of the heat transfer coefficients used in the function, the temperatures on the surface of the cast strand were measured under real casting conditions.

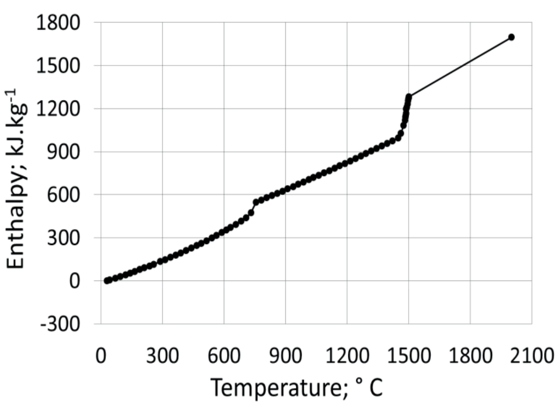
2.2. Thermo-physical and thermo-dynamic properties of steel

To achieve the relevant numerical results, it is necessary to have correctly defined thermo-physical and thermo-dynamic properties of the steel. The properties can be determined theoretically with use of empirical equations, or with use of some thermodynamic solver. The phase transformation temperatures should be verified by different methods. For determination of liquidus and solidus temperature and heat capacity, the thermal analysis can be used [25]. The reason for verification of the theoretically defined thermodynamic properties is due to the fact that the thermodynamic database can calculate with the equilibrium state during the determination of phase transformation temperatures. The steel is, however, a multi-component heterogeneous material with difficult structure and the metallurgical production process can lead to evolution of many types of non-metallic phases. These non-metallic phases might have different physical properties than the metal matrix, which as a consequence influences the values of phase transformation temperatures and also the character of transformation [26].

Continuous casting process of steel containing approx. 0.35 wt.% C was simulated. Due to the fact that the simulated steel grade was not included in the basic material database of the simulation programme, the integrated thermodynamic database was used to calculate the thermodynamic properties. The thermo-dynamic and thermo-physical properties depend on the temperature.

The liquidus temperature of the steel was 1,771 K, and the solidus temperature was 1,721 K. Fig. 3 shows the calculated thermo-dynamic properties of steel, such as density, thermal conductivity and enthalpy.





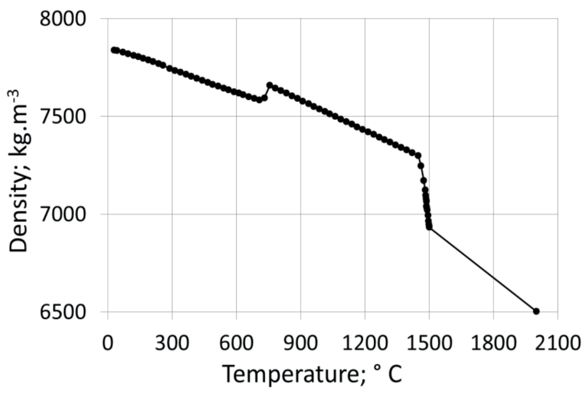


Fig. 3. Calculated thermo-dynamic properties of the studied steel

2.3. Boundary conditions, operating conditions, type of computation

The boundary conditions, such as casting speed and casting temperature, were defined according to the plant data. The ambient temperature was 298 K. The level of the steel in the mould was 80% from the height of the mould. The temperature difference between the inlet and outlet of cooling water in the mould was 12 K. The gravity was 9.81 $m^{\cdot s^{-1}}$. The standard pressure was considered to be 101,325 Pa. For simulation, the traveling boundary algorithm was used. Numerical solution of the mathematical model of solidification of the continuously cast steel strand was performed using the finite element method.

3. Discussion of the obtained results

During the first stage of an extensive modelling research, the attention of numerical modelling was focused on definition of the 3D geometry of the round billets, on prediction of the temperature profiles, on thickness of the solidified shell at the end of the mould and on prediction of the metallurgical length.

3.1. Type of geometry and computational mesh

Computation was carried out on half of the entire geometry (Fig. 4). The reason, why to use only one symmetrical half of the geometry is shorter computation time at a much finer mesh-work. The created geometry includes the entire curved section and also the straight section of the strand. In order to simulate the metallurgical length, the geometry must be drawn only up to the end of the tertiary cooling zone. The level of steel in the mould was marked from its upper edge. The nozzle was not considered in the heat calculation. The secondary cooling and the rolls were replaced with the User Function of thermal boundary condition.

The structured volume mesh containing a hexagonal and a wedge element was prepared (detail in Fig. 4). Density of the mesh was designed with regard to thermal gradients in the mould and in the strand.

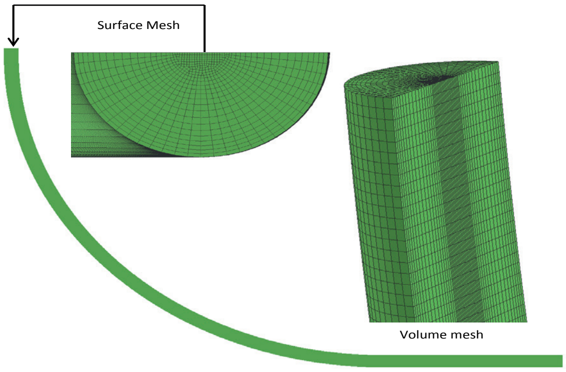


Fig. 4. Geometry of the round format from continuous casting machine and the detailed view of the computational mesh

3.2. Surface vs. measured temperatures

Fig. 5 shows a temperature field on the surface of the strand. The temperature change along the casting strand was displayed using the Plot function with pick node defined at the end of the billet (Fig. 6). This node can describe the temperature change in time. The obtained profile of the temperature change (Fig. 7) was compared with the information from the real plant measurement of temperatures on the surface of the cast strand using the pyrometers.

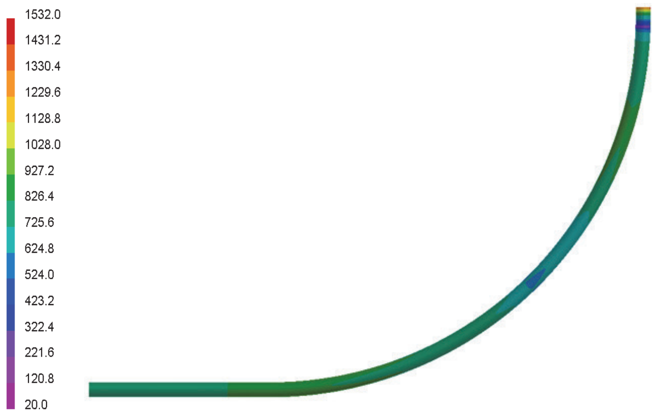


Fig. 5. The surface temperature in °C

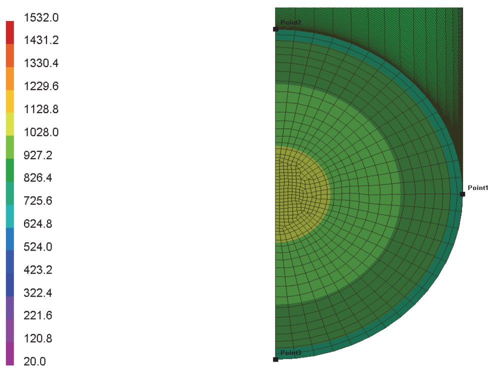


Fig. 6. Detailed view of the pick node for displaying the change of the temperature in time dependence

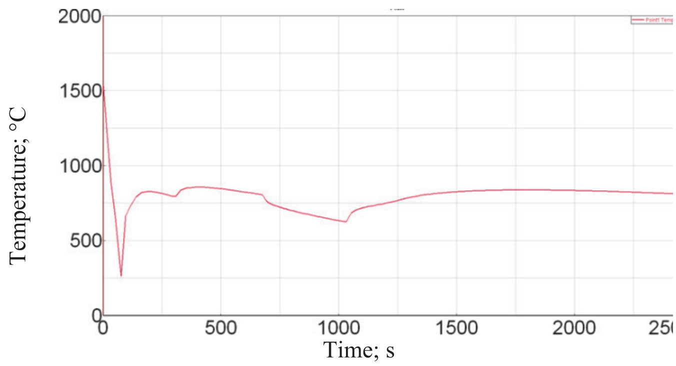


Fig. 7. The temperature profile along the casting strand during the casting displayed by the pick node

3.3. Metallurgical length and thickness of the shell at the end of the mould

During evaluation of results the main attention was paid to the assessment of thickness of the solidified shell at the end part of the mould, and of the metallurgical length. The thickness of the solidified shell, particularly it is essential its uniformity, for example for formation of the surface depressions, cracks and the risks of breakout. Thickness of the solidified shell at the end of the mould was 23 mm (detail in Fig. 8). The metallurgical length with the given computation parameters was 12.9 m (Fig. 8).

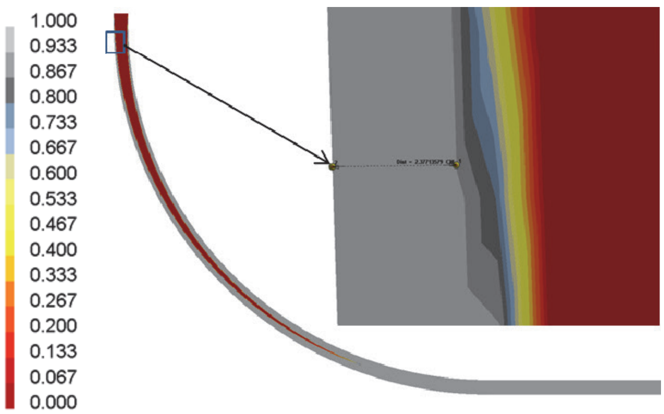


Fig. 8. Prediction of the metallurgical length (12.9 m) and the thickness of solidified shell at the end of the mould (which was approx. 23 mm) using Fraction Solid

4. Conclusion

The aim of numerical modelling using the finite element method was to verify the temperature field, the thickness of the shell at the end of the mould and the metallurgical length in continuously cast round steel billets with a diameter of 400 mm. Using the numerical modelling, it was found that:

1. the geometry for simulation of the solidification of the continuously cast billets depends on the type of required results; for prediction of the metallurgical length it is possible to use the entire geometry of the casting strand, but it is useful to apply the condition of symmetry in order to achieve a shorter calculation time;

2. the quality of the numerical results depends on the accuracy of description of the thermodynamic properties of the steel, or on the defined conditions of the heat transfer in the primary and secondary cooling zones;
3. experimental heat transfer coefficients obtained from the measurement and implemented into the user function describing the heat transfer along the casting strand in the secondary cooling zone led to slightly different surface temperatures achieved by pyrometers. The differences were probably related to the measuring methods and to the actual real casting conditions.

The next stage of the research will be focused on the validation of the temperature profile along the casting strand. Also, the porosity, the risk of the cracks and the character of the temperature field with flow calculation (the nozzle consideration) will be evaluated.

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