INFLUENCE OF CHEMICAL COMPOSITION OF CAST STEEL ON TEMPERATURE FIELD OF CONTINUOUSLY CAST BILLETs

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Abstract
Continuous casting machines produce dozens of various steels that are divided into classes according to norms or standards and further sorted into groups with respect to the carbon content. In steel classes, the chemical composition and its allowed range are prescribed and they significantly affect thermophysical properties of steel, e.g. the thermal conductivity, specific heat, density, enthalpy, contractility and viscosity. The chemical composition and its change have also an impact on temperatures of phase and structural changes, e.g. temperatures of solidus and liquidus. The thermophysical properties of steel can be determined by experiments that is, however, in case of many steel grades fairly difficult and expensive, and therefore numerical solidification models are often used. The aim of paper is the study of the chemical composition influence on thermophysical properties of steel as well as on the final temperature field of cast billet for three grades of steel from a particular class having various carbon contents. For this purpose the IDS Solidification Software and the dynamic 3D model of temperature field have been utilized. The results of temperature fields are presented for the 200 x 200 mm billet cast in Železiarne Podbrezová, a.s. The paper demonstrates the software tools developed for described purposes in Matlab and Delphi. The presented study can be utilized for the determination of the chemical analysis precision for numerical models of temperature field and for further optimization of cast billet quality.

Key words: diverted chemical composition, numerical model, temperature field, continuous casting

1. INTRODUCTION
Nowadays, numerical models and simulation tools of a transient temperature field of continuously cast slabs, billets or blocks are commonly being used in steelworks over the world in order to control, monitor and to optimize the production of steel. Many various grades of steel with a different chemical composition and particularly with a different content of carbon are usually cast, and therefore the numerical models and other simulation tools have to be easily adaptable to a particular grade of steel being cast. This is usually accomplished by input parameters to the numerical model of temperature field that consist among other inputs of thermophysical parameters of steel, chiefly of the enthalpy, thermal conductivity, specific heat and density. It has been proven \cite{1} that the chemical composition and particularly the carbon content of steel considerably influence courses and dependences of mentioned thermophysical properties on the temperature, temperatures of phase and structural changes of steel (e.g. liquidus and solidus temperatures, the temperature of peritectic transformation, etc.), and therefore also the formation of the entire transient temperature field of continuously cast steel. Owing to a deflection of chemical composition or its wrong determination, a prospective difference between the temperature field of cast steel calculated by a numerical model and the real temperature field of cast steel can be a reason of poor quality, different structure, loss of material and mechanical properties or even defects of cast steel and final products.

The aim of the article is the investigation of an influence of diverted chemical composition on the temperature field formation and the thermal behaviour of continuously cast steel. The analysis deals with three different
grades of steel according to the carbon content, particularly with the 0.08 %, 0.18 % and 0.47 % of carbon that are cast in Železiarne Podbrezová, Slovakia. For this purpose the in-house 3D dynamic solidification model is utilized and the thermophysical properties of cast steel are determined by the solidification analysis package IDS [2] according to a particular chemical composition.

2. DYNAMIC MODEL OF TEMPERATURE FIELD OF CAST STEEL BILLET

The analysis of influence of diverted chemical composition is performed by utilizing the transient numerical model that is able to calculate the temperature field of entire cast billet from the meniscus inside the mould to the cutting torch where billets are cut to a desired length. The solidification of steel blank is driven by the transient heat and mass transfer. In the case the mass transfer is neglected and the heat transfer in the blank via the conduction is considered to be dominant, the temperature field of cast blank is governed by the Fourier-Kirchhoff equation

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

(1)

where $H$ is the volume enthalpy, $T$ represents the temperature, $\lambda$ is the thermal conductivity, $v_z$ denotes the velocity component of cast billet in the longitudinal direction, $t$ is time, and $x$, $y$, and $z$ are spatial coordinates. The volume enthalpy $H$, which is a thermodynamical function dependent on the temperature, includes the latent heat of phase changes and is defined as follows [3]

$$H(T) = \int_0^T \left( \rho c - \rho L_f \frac{\partial f_s}{\partial T} \right) d\theta$$  

(2)

where $\rho$ is the density, $c$ is the specific heat, $L_f$ denotes the latent heat and $f_s$ is the solid fraction.

The numerical model is then established by applying the control volume method and the explicit discretization scheme [4] and the unknown volume enthalpy in a node $(i, j, k)$ at time $t + \Delta t$ is given by

$$H_{i,j,k}^{t+\Delta t} = H_{i,j,k}^t + \frac{\Delta t}{\Delta x \Delta y \Delta z} \left( QZ_{i,j,k} + QZ_{i,j,k}^{L} + QY_{i,j,k} + QY_{i,j,k}^{L} + QX_{i,j,k} + QX_{i,j,k}^{L} \right)$$  

(3)

where $QX$, $QX^L$, $QY$, $QY^L$, $QZ$ and $QZ^L$ are the heat flows through the control volume. For the heat flow $QZ$ in the direction of casting, the $QZ$ also has to include the volume enthalpy of an incoming melt that enters to the control volume through the control surface and is proportional to the casting velocity $v_z$.

Since the problem is symmetric with respect to the longitudinal vertical plane, only one half of billet is considered. In order to correctly complete the model, the initial and boundary conditions [4] (at the level of cast steel in the mould, at the plane of symmetry, inside the mould, within the secondary and tertiary cooling zones and beneath the rollers) must be provided. For details of the numerical model, see [4].

3. INVESTIGATED GRADES OF STEEL

For the analysis three grades of steel, which represent a main part of steel production cast in Železiarne Podbrezová, Slovakia, were chosen: the grade S235JR with the 0.08 % of carbon (unalloyed steel for constructions and welding), the grade S355J2G3 with the 0.18 % of carbon (unalloyed fine-grained steel for constructions and welding) and the grade C45 with the carbon content of 0.45 % (carbon steel for constructions, refining and surface hardening). For all three grades of steel, three chemical compositions of each are considered: the real chemical composition (REAL) of cast steel given by the chemical analysis of a particular meltage and the minimal (MIN) and maximal (MAX) chemical composition given by the standards and norms. The investigated steel grades and their chemical composition of main elements are summarized in Tab. 1.
Tab. 1 Real, minimal and maximal chemical composition of investigated steel grades

<table>
<thead>
<tr>
<th>Grade of steel</th>
<th>Chemical composition of cast steel [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>S235JRH</td>
<td>REAL</td>
</tr>
<tr>
<td></td>
<td>MIN</td>
</tr>
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<td></td>
<td>MAX</td>
</tr>
<tr>
<td>S355J2G3</td>
<td>REAL</td>
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<tr>
<td></td>
<td>MIN</td>
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<tr>
<td></td>
<td>MAX</td>
</tr>
<tr>
<td>C45</td>
<td>REAL</td>
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<td></td>
<td>MIN</td>
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<td></td>
<td>MAX</td>
</tr>
</tbody>
</table>

4. THERMOPHYSICAL PROPERTIES OF STEEL

A proper and precise determination of thermophysical properties is a necessary condition to obtain the accurate and reliable prediction of the temperature field of cast billets by using the dynamic model. From Eq. (1) and (2) it is obvious that the crucial role of thermophysical properties mainly play the volume enthalpy $H$, specific heat $c$, thermal conductivity $\lambda$ and the density $\rho$.

![Graph](image-url)

**Fig. 1** Volume enthalpy, specific heat, thermal conductivity and density for the steel grade S235JRH

The thermophysical properties of all grades of steel were determined numerically by using the solidification analysis package IDS whose results were validated [2]. The calculated dependences of the volume enthalpy, specific heat, thermal conductivity and the density on the temperature for the steel grade S235JRH (REAL) are shown in Fig. 1. The phase fraction diagram for the steel grade S355J2G3 (REAL), which can be used for the determination of steel structure and fractions of particular phases at a desired temperature, is shown in Fig. 2. The influence of diverted chemical composition on the temperature-dependent courses of the volume enthalpy (steel grade C45, the temperature range of mushy zone), specific heat (steel grade S355J2G3, the temperature range of structural change in a solid state) and the thermal conductivity (steel grade S235JRH, the entire temperature range) are presented in Fig. 3, Fig. 4 and Fig. 5, respectively.

The performed analysis proved that there exists a significant influence of diverted chemical composition on the thermophysical properties: a higher content of alloying elements causes a shift of temperatures of phase changes in both the liquid-solid (solidus and liquidus temperatures) and solid (e.g. temperatures of proeutectoid ferrite and pearlite formations) states to lower temperatures, see Fig. 3, Fig. 4 and Fig. 5.
Moreover, the chemical composition also affects the temperature ranges of these phase changes, particularly the higher content of alloying elements makes the wider temperature range between solidus and liquidus temperatures, see Fig. 3. The perturbation of chemical composition also influences the particular values of thermophysical properties dependent on the temperature. However, it is difficult to state this influence generally, since the dependence differs from a particular thermophysical property and from a temperature range, see Fig. 3, Fig. 4 and Fig. 5.

5. ANALYSIS AND RESULTS

The analysis of influence of diverted chemical composition was performed by utilizing the transient numerical model for mentioned three steel grades (see Tab. 1) that are cast in Železiarne Podbrezová, Slovakia [5]. For the study the 200 x 200 billet with the casting speed 0.9 m/min were chosen. The radial slab caster includes the secondary cooling that consists of three cooling zones (in figures denoted by S-0, S-1 and S-2) with 96 cooling water nozzles in total, and two straightening mills (in figures denoted by SM-1 and SM-2).

The developed temperature field on the top surface (small radius) for the steel grade C45 (REAL) is shown in Fig. 6. The detail of surface temperatures in the middle of top surface along the blank (corresponding to
**Fig. 6** with the width equalled to 0 mm) for the steel grade C45 (REAL) and its minimal (MIN) and maximal (MAX) chemical compositions (see Tab. 1) are pictured in **Fig. 7**.

It can be seen in **Fig. 7** that the chemical composition has an influence on the courses on the surface temperatures of cast billet. Particularly, the steel composition with the minimal content of elements (MIN) leads to the higher surface temperatures (a rise about 3 °C) with respect to the real composition of steel grade C45 (REAL). On the contrary, steel with the maximal chemical composition (MAX) leads to the lower surface temperatures (a drop about 6 °C) with respect to the steel grade C45 with the real chemical composition (REAL), see **Fig. 7** and Tab. 1.

The thermal behaviour in the core of cast billet (a horizontal longitudinal cross-section of billet) for the steel grade S235JRH is depicted in **Fig. 8**. The curves made by a coloured solid line represent the isosolidus curves where the last rest of liquid steel (meltage) is transformed to the solid phase. The maximal length of isosolidus (i.e. for the width equalled to 0 mm) is called the metallurgical length that is an important parameter of continuous casting. Further, the curves made by a coloured dash line represent the isoliquidus curves where the first grain of steel is solidified. As can be seen in **Fig. 8** the higher content of elements in the steel composition (MAX) causes a shift of isosolidus curve to the right (becomes longer) thereby the metallurgical length increases from 12.9 m (REAL) to 13.3 m (MAX). Furthermore, steel with the maximal content of elements also brings about a shift of isoliquidus curve to the left (becomes shorter), and therefore the mushy zone is enlarged (the width of mushy zone in the broadest position for the MAX chemical composition of S235JRH is about 3.4 m and for the REAL chemical composition of S235JRH is about 2.7 m), see **Fig. 8**.

On the contrary, the minimal chemical composition of S235JRH (MIN) causes a shift of isosolidus to the left (becomes shorter) and a shift of isoliquidus to the right (becomes longer) thereby the mushy zone is reduced with the width in the broadest position of about only 1 m, see **Fig. 8**.

Periods of solidification (the local width of mushy zone related to the casting velocity) for the steel grade S355J2G3 (REAL) and its MAX chemical composition are shown in **Fig. 9** and **Fig. 10**, respectively. From the figures it can be seen that the chemical composition has a great influence on the solidification process.
through the entire cross-section of cast billet. In the case of REAL the solidification on surfaces of billet is very fast and it slows down when approaching the core of billet, see Fig. 9. However, in the case of MAX the longest local period of solidification is not in the core but in four points out of the core, see Fig. 10.

![Fig. 9 Period of solidification for S355J2G3 (REAL)](image1)

![Fig. 10 Period of solidification for S355J2G3 (MAX)](image2)

6. CONCLUSION

The influence of chemical composition and its deflection on the temperature field of continuously cast slabs was investigated by utilizing the numerical model of temperature field of cast steel and the results of the solidification analysis package IDS. The results showed that the chemical composition of steel has an impact on courses of thermophysical properties in the temperature range of the mushy zone and of the phase change in the solid state. Due to a diverted chemical composition the final temperature field of cast billet is also influenced through the transition of thermophysical properties. The analysis confirmed that the higher content of elements in steel causes lower surface temperatures of cast blank and shifts the temperatures of phase changes to lower values. Moreover, the chemical composition with the higher content of elements also enlarges the mushy zone and makes the metallurgical length longer. In addition, the chemical composition has a considerable influence as well on the local period of solidification through the cross-section of cast blank. Relevant conclusions can be also made for steel with the minimal chemical composition. All the described information gained by using the transient numerical model of temperature field can be utilized for the control, setting or quality optimization of continuous casting and final products.

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REFERENCES


