Study of thermal behaviour of continuously cast billets

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Abstract In continuous casting the quality of cast steel slabs and billets, thermal stress, surface defects and cracks formation are highly dependent on the temperature distribution along the entire continuously cast blank. The main attention is usually paid to the surface temperatures and particularly to the corner temperature distributions. However, from the technological point of view the temperature distribution in the core of cast blank, which is highly related to the metallurgical length and to the unbending process, is very important as well. Therefore, monitoring of temperature field of cast blanks, its prediction by using numerical models as well as controlling and optimization tasks of secondary cooling strategy are priority tasks for technologists, quality engineers, and operators of continuous casting machine. The paper is aimed at the thermal analysis and the investigation of temperature field of cast billets by utilizing the original numerical model of temperature field of continuously cast steel billets. In particular, three grades of steel with a different carbon content and the 200 x 200 mm billets, which are cast in Železiarne Podbrezová in Slovakia, are considered. The performed study and presented software tools can be used by engineers to enhance the quality and productivity of continuously cast steel and to improve the competitiveness of steelworks.

1 Introduction

Final quality of continuously cast steel as well as thermal stress deformation, surface defects or cracks formation are mainly influenced by the temperature distribution inside the cast blank, e.g. by large temperature gradients in corners of cast rectangular blank, or by the straightening related to the metallurgical length. Due to these reasons, it is therefore worth to utilize numerical models of continuous casting in order to predict, monitor, control and optimize the temperature field of cast product which helps to minimize an occurrence of problems mentioned above, [4]. Generally, the temperature fields of different cast steel grades, which are cast with identical casting and operating parameters and conditions, are different. This is mainly caused by different values of thermophysical properties of cast steel that are significantly related to a particular chemical composition of steel, particularly to the carbon content.

The paper is aimed at the investigation of thermal behaviour of continuously cast billets by utilizing the original model of temperature field of cast billets. For the analysis, 200 x 200 mm billets and three steel grades with the carbon content of 0.08 %, 0.18 %, and 0.45 %, which represent the main production of Železiarne Podbrezová in Slovakia, were chosen.

2 Numerical model of temperature field of steel billets

The study of thermal behaviour was performed by utilizing the original numerical model of continuously cast steel billets that calculates the transient temperature field of cast blank along the entire caster: from the meniscus inside the mould through the mould, secondary and tertiary cooling to the cutting position where billets are cut by the torch to particular lengths.

From the physical point of view the solidification of cast billets is governed by phenomena of heat and mass transfer. If the mass transfer is considered to be minor and negligible, then heat transfer inside the cast billet through the conduction mechanism is taken into account as major. Thus, the temperature distribution of cast steel billet is driven by the Fourier-Kirchhoff equation

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

where T represents the temperature, H stands for the volume enthalpy, k is the thermal conductivity, v_z denotes the casting velocity, t is time, and x, y, and z are spatial coordinates. In Eq. (1) the thermodynamical function of volume enthalpy is introduced in order to include the latent heat of phase and structural changes that is being released during the solidification.

The numerical model of transient temperature field of cast billet [3] is then constituted by utilizing the control volume method applied to Eq. (1) that allows a worth physical insight to the discretization procedure. The time derivative in Eq. (1) is discretized by using the explicit numerical scheme. Since Eq. (1) contains the temperature and enthalpy variables that are both unknown and linked to each other, it is necessary first to calculate the enthalpy, and then the corresponding temperature from the already known value of the volume enthalpy is determined according to the temperature-enthalpy relationship of particular steel grade.

Due to the symmetry with respect to the longitudinal vertical plane, only one half of cast billet is studied. From mathematical point of view, the initial and boundary conditions are required in order to correctly formulate the studied problem. Therefore, the initial temperature distribution of entire billet and boundary conditions in the mould at the level of cast steel, 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 numerical model and its implementation, see [3, 4].

3 Investigated steel grades

The thermal analysis of continuously cast billets was performed for three grades of steel [1] that represent a major part of steel production in Železiarne Podbrezová in Slovakia: unalloyed steel for construction and welding S235JRH with the carbon content of 0.08 %, unalloyed fine-grained steel for construction and welding S355J2G3 with the carbon content of 0.18 %, and carbon steel for construction, refining and surface hardening C45 with the carbon content of 0.45 %. The chemical composition of investigated steel grades is shown in **Tab. 1**.

Tab. 1 Chemical composition (major elements) of investigated steel grades

Steel grade	Chemical composition of cast steel [%]										
	C	Si	Mn	P	S	Cr	Ni	Cu	Al	Ti	V
S235JRH	0.070	0.21	0.44	0.011	0.007	0.06	0.05	0.17	0.026	0.002	0.004
S355J2G3	0.187	0.22	1.17	0.016	0.012	0.06	0.09	0.26	0.022	0.002	0.004
C45	0.455	0.23	0.63	0.009	0.011	0.05	0.05	0.19	0.017	0.021	0.004

The solidification analysis package IDS [2] was utilized for the determination of thermophysical properties of steel grades summarized in **Tab. 1**. As it can be seen from Eq. (1), the volume enthalpy, thermal conductivity, specific heat, density and their dependences on the temperature are crucial inputs to the numerical model. Hence they are required to be precisely determined in order to obtain an accurate and reliable prediction of temperature field of cast billets.

4 Analysis of thermal behaviour of cast steel billets and discussion

The thermal analysis was carried out for 200 x 200 mm billets of three steel grades summarized in **Tab. 1** that are cast in Železiarne Podbrezová in Slovakia. The radial billet caster with three cooling zones (denoted by S-0, S-1, and S-2), 96 cooling water nozzles inside the secondary cooling and two straightening mills (denoted by SM-1 and SM-2) are considered. The casting temperature and casting speed are 1,555 °C and 0.9 m/min, respectively, for all grades.

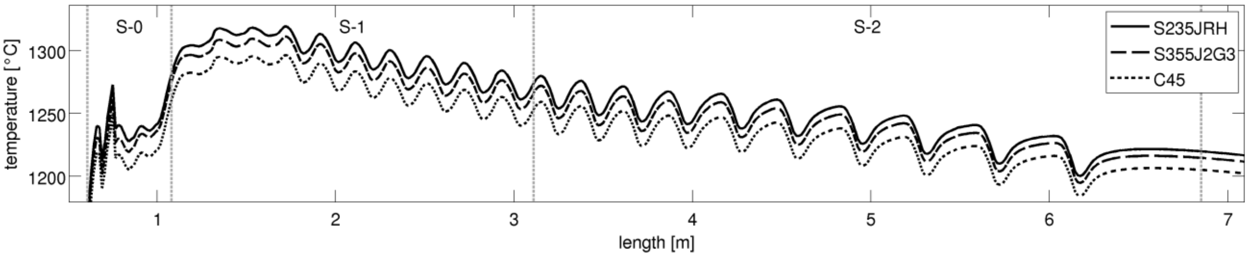

Fig. 1 Top surface (small radius) temperatures beneath cooling nozzles within the secondary cooling

The surface temperatures within the secondary cooling beneath the cooling nozzles and at the corner are shown in **Fig. 1** and **Fig. 2**, respectively. Beneath the nozzles the surface temperature oscillates due to the effect of cooling nozzles. The grade C45 reaches the lowest surface temperatures, and conversely the grade S235JRH attains the highest values of surface temperatures, the difference is about 20 °C. As the length position increases, the temperature fluctuations becomes larger due to the increasing distance of nozzles, see **Fig. 1**.

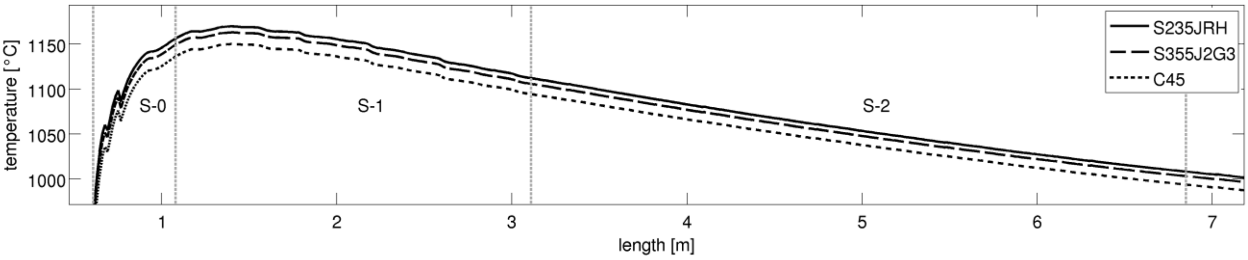

Fig. 2 Corner temperatures (top surface – small radius) within the secondary cooling

The corner temperatures within the secondary cooling do not exhibit fluctuations as the temperatures beneath the nozzles do. It indicates a tiny direct influence of used cooling nozzles at corners of billets. Similarly to the case of temperatures beneath nozzles, the grade C45 keeps the lowest temperatures at the corner whereas the grade S235JRH the highest ones, see **Fig. 2**. However, the difference between the corner temperatures of steel grades is only 8 °C.

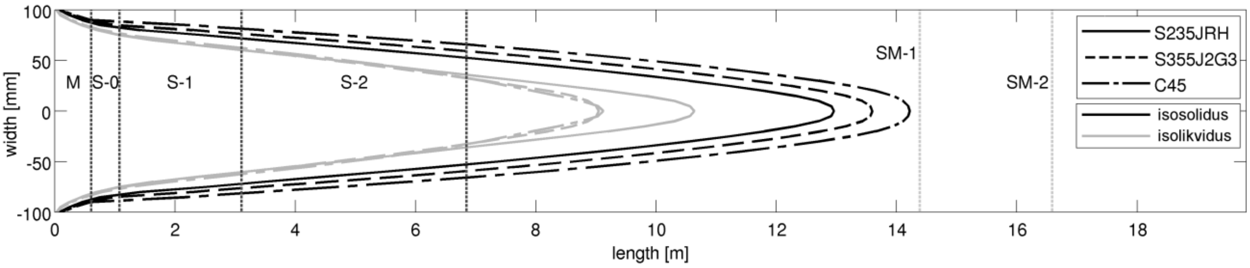

Fig. 3 Isosolidus and isoliquidus curves.

The isosolidus and isoliquidus curves for all three steel grades are shown in **Fig. 3**. A significant influence of chemical composition to the isosolidus and isoliquidus curves, and thus to the metallurgical length can be observed [1]. The grade C45 with 0.45 % of carbon results in a widest mushy zone whereas the grade S235JRH (0.08 % of carbon) to the narrowest one, see **Fig. 3**.

Local period of solidification, which is the width of mushy zone in the longitudinal direction related to the casting velocity, is shown in **Fig. 4** where an interesting phenomenon during the solidification and thermal behaviour can be observed. In the case of grade S355J2G3 the billet surface is solidified immediately inside the mould and time needed to the solidification increases when approaching the core of billet. Nonetheless, the solidification process for grades C45 and particularly for S235JRH behaves differently: the solidification takes the longest period in four points outside the core of cast billets, see **Fig. 4**.

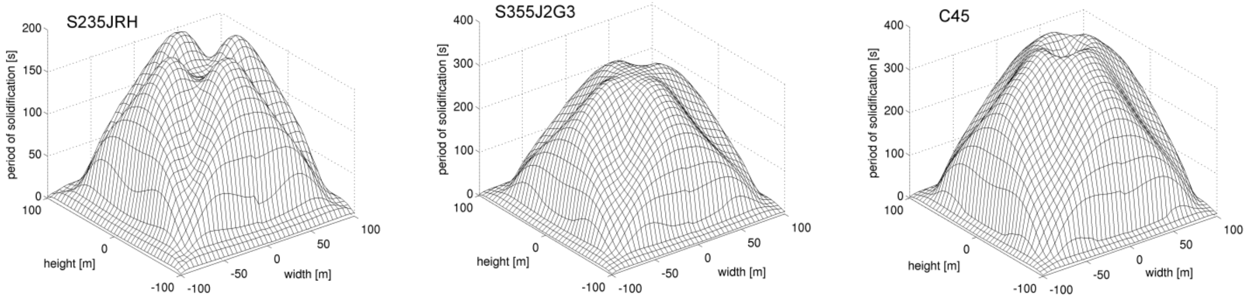

Fig. 4 Local periods of solidification process.

5 Conclusion

The analysis of thermal behaviour of continuously cast steel billets was performed by utilizing the original numerical model of temperature field. Three steel grades with the different carbon content were considered. The study showed that the chemical composition and the carbon content have a significant influence on thermal behaviour of continuously cast steel billets. Steel with lower content of carbon tends to attain higher temperatures, both beneath nozzles and at corners, and the mushy zone is narrower for lower content of carbon. On the contrary, steel with the higher content of carbon reaches lower surface and corner temperatures, and the mushy zone becomes wider. The analysis also showed that a direct influence (temperature fluctuations along the billet) of used cooling nozzles at corners for the particular caster configuration is minor. Further, a particular chemical composition and carbon content have also an influence on the local solidification period that can affect chiefly the structure in the core of cast billets.

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