STUDY OF THERMAL BEHAVIOUR OF CONTINUOUSLY CAST BILLETS

Lubomír Klimeš*, Josef Štětina*, Ľudovít Parilák**, Pavol Buček**

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 issues 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 different carbon content and the 200×200 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.

Keywords: *continuous casting, temperature field, thermal behaviour, dynamic solidification model*

1. Introduction

The final quality of continuously cast steel as well as the thermal stress and 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 blanks, or by the straightening process related to the metallurgical length) and by the solidification of steel (e.g., the period of solidification through the cross section, the width of the mushy zone where both the liquid and solid phases coexist). Due to these reasons, it is therefore useful to utilize dynamic solidification 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 [1].

During the last decade, numerical models of solidification have become common tools used in steelworks for the production control. One of main advantages of the dynamic solidification models is the ability to analyse the thermal behaviour of cast blanks and to check the response of the caster to various operating conditions and options without any influence

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of the real steel production and of the caster. Furthermore, the dynamic solidification model can be also utilized for optimization of the caster and production parameters, e.g., to determine the optimal casting speed or the optimal cooling strategy in the secondary cooling zone of the caster. The numerical models can be also utilized for the investigation of the thermal stress of cast blanks: frequently with the use of the finite difference and the finite element methods [2, 3, 4, 5] as well as with the use of specialized techniques, e.g., the front tracking boundary element method [6], for the thermal and mechanical analysis of the mould [7, 8] and for the investigation of materials properties, quality, and cracks formation [9, 10, 11]. Another utilization of dynamic solidification models is for optimization tasks of continuous steel casting process, e.g., to determine the optimal casting velocity, optimal types of cooling nozzles and their positioning in the secondary cooling, or optimal flow rates of water flowing through nozzles [12, 13, 14, 15].

Generally, the temperature field and the temperature distribution of blanks of different steel grades, which are cast with identical casting and operating parameters and conditions, are different. Also the solidification process of steel from the melt to the solid blank, behaves differently for various steel grades with a different chemical composition [9]. This is mainly caused by different values of thermophysical properties of cast steel that are significantly related to a particular chemical composition of steel, mainly to the carbon content [16]. Therefore it is a crucial task in modelling of continuous casting to provide the correct dependency of the thermophysical properties on the temperature according to the particular chemical composition of steel being cast. This can be done experimentally, which is fairly difficult, expensive and time-consuming, or with the use of the analytical solidification software [17]. Such analysis packages enable the determination of thermophysical properties according to a given chemical composition that can be obtained, e.g., by the chemical analysis of a sample from the tundish, or from the ladle.

The paper is aimed at the investigation of thermal behaviour of continuously cast billets on the radial slab caster in Železiarne Podbrezová in Slovakia. The analysis was carried out with the use of the original model of temperature field of cast billets. For the analysis, 200×200 mm billets and three standard steel grades S235JRH, S355J2G3, and C45 with the nominal carbon content of 0.08 %, 0.18 %, and 0.45 %, respectively, which represent the main production of Železiarne Podbrezová, 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 [18, 1] that enables the calculation of the transient temperature field formation of cast billets along the entire caster: from the meniscus (the pouring level of the melt inside the mould) through the mould, the secondary and tertiary cooling zones to the cutting position where billets are cut by the torch to particular lengths applicable for next steelmaking processing, e.g., for rolling. The numerical model fully accepts all the dimensions, parameters and configuration of the caster in Železiarne Podbrezová. The mould and the secondary cooling zone (positioning of cooling nozzles and of a system of supporting rollers system) of the caster is schematically shown in Fig. 1.

From the physical point of view, the solidification process of cast billets is governed by phenomena of heat and mass transfer. If the mass transfer is considered to be minor and is neglected, then heat transfer inside the cast billet through the conduction heat transfer mechanism is taken into account as major. Thus, the transient evolution of the temperature distribution of cast steel billet is driven by the Fourier-Kirchhoff equation [19, 20]

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

where T [K] represents the temperature, H [$\mathrm{J\,m^{-3}}$] stands for the volume enthalpy, k [$\mathrm{W\,m^{-1}\,K^{-1}}$] is the thermal conductivity, v_{z} [$\mathrm{m\,s^{-1}}$] denotes the casting velocity, t [s] is time, and x, y and z [m] are spatial coordinates. The thermodynamical function of the volume enthalpy H in Eq. (1) is introduced in order to include the latent heat of phase and structural changes that is released during the solidification process of steel [19, 21]. The volume enthalpy, which characterises both the sensible and latent heat of steel in the given temperature related to the unit volume, can be defined as follows [19]

$$H(T) = \int\limits_{T_{\mathrm{ref}}}^{T} \left(\varrho\,c - \varrho\,L_{\mathrm{f}}\,\frac{\partial f_{\mathrm{s}}}{\partial \theta}\right) \mathrm{d}\theta \tag{2}$$

where ϱ [$\mathrm{kg\,m^{-3}}$] is the density, c [$\mathrm{J\,kg^{-1}\,K^{-1}}$] is the specific heat, L_{f} [$\mathrm{J\,kg^{-1}}$] is the latent heat of phase change and f_{s} [1] is the solid fraction representing the amount of the solid phase of steel in a particular temperature. The temperature T_{ref} is the reference temperature for the calculation of the volume enthalpy. The reference temperature is usually considered to be 0 K or the ambient temperature. Note that the volume enthalpy approach is not the only technique for the phase change modelling but it offers a better numerical stability and accuracy in comparison to other methods, e.g., the effective heat capacity method [19, 22].

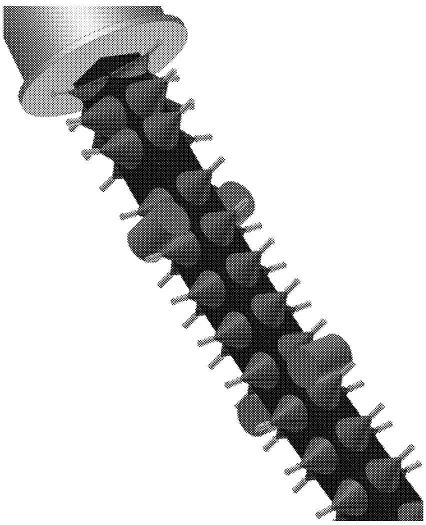

Fig.1: Schematic view to the primary (mould) and secondary cooling zones of the caster

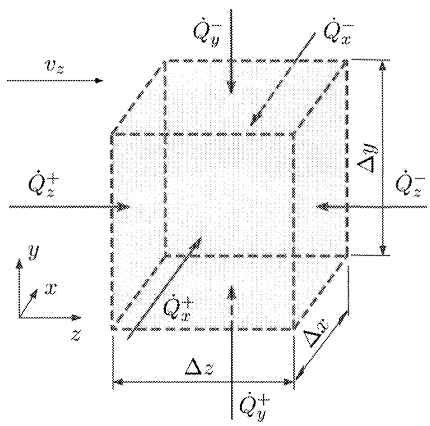

Fig.2: Energy balance of control volume [23]

The numerical model of transient temperature field of cast billet is then constituted by utilizing the control volume method applied to Eq. (1) that allows a worth physical insight to the discretization procedure. The control volume method is based on establishing the energy balance for all defined control volumes of cast billet, see Fig. 2. 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 first necessary to calculate the volume enthalpy. The corresponding temperature from the already known value of the volume enthalpy is then determined according to the temperature-enthalpy relationship of particular steel grade. The general explicit formula for the volume enthalpy of the control volume (i,j,k) in the time step $t+\Delta t$ is then given as

$$H^{t+\Delta t}_{i,j,k} = H^{t}_{i,j,k} + \frac{\Delta t}{\Delta x\,\Delta y\,\Delta z}\,(\dot{Q}^{+}_{\mathrm{x}} + \dot{Q}^{-}_{\mathrm{x}} + \dot{Q}^{+}_{\mathrm{y}} + \dot{Q}^{-}_{\mathrm{y}} + \dot{Q}^{+}_{\mathrm{z}} + \dot{Q}^{-}_{\mathrm{z}}) + v_{\mathrm{z}}\,\Delta t\,\frac{H^{t}_{i,j,k-1} - H^{t}_{i,j,k}}{\Delta z} \quad (3)$$

where Δx, Δy, Δz and Δt are spatial and time discretization steps, respectively, and $\dot{Q}$ are the heat fluxes where the subscript denotes the heat flux direction (the axis to which the heat flux is parallel) and the sign in the superscript indicates the positive or negative orientation of the heat flux with respect to the corresponding axis of the coordinate system.

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 problem. Therefore the initial temperature distribution of entire billet and boundary conditions in the mould at the level of cast steel (the pouring temperature), at the plane of symmetry and at the cutting torch plane (assuming zero heat flux), inside the mould (heat flux of the heat withdrawal), within the secondary and tertiary cooling zones and beneath the rollers (usually combination of convective and radiation heat transfer mechanisms) must be provided. For details of the numerical model and its implementation, see [18].

3. Investigated steel grades and thermophysical properties

The thermal analysis of continuously cast billets was performed for three standard grades of steel that represent a major part of steel production in Železiarne Podbrezová. The chemical compositions were determined experimentally by the chemical analysis of particular steel melts: unalloyed steel for construction and welding S235JRH with the carbon content of 0.070 %, unalloyed fine-grained steel for construction and welding S355J2G3 with the carbon content of 0.187 %, and carbon steel for construction, refining and surface hardening C45 with the carbon content of 0.455 %. The chemical composition of investigated steel grades obtained by the chemical analysis from particular melts is shown in Tab. 1.

Steel grade	Chemical composition of cast steel [wt. %]										
	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

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

As already mentioned the accurate determination of the thermophysical properties and their dependency on the temperature are important tasks in modelling of continuous steel casting. Moreover, the previous analysis [16] proved a significant dependency of the thermophysical properties on the chemical composition. Therefore the thermophysical properties are needed to be determined according to the chemical composition of steel being cast, i.e., steel in the tundish. This can be ensured, e.g., by the chemical analysis of a sample from the tundish that can be carried out in the case of new incoming melt from the ladle.

Due to the above discussed issues, the solidification analysis package IDS (version 1.3.1), which results were verified with experiments [17, 24], was utilized for the determination of thermophysical properties of steel grades summarized in Tab. 1. As 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 since these properties straightforwardly influence the entire temperature field formation. Hence the mentioned thermophysical properties are required to be precisely determined in order to obtain an accurate and reliable prediction of the temperature field of cast billets.

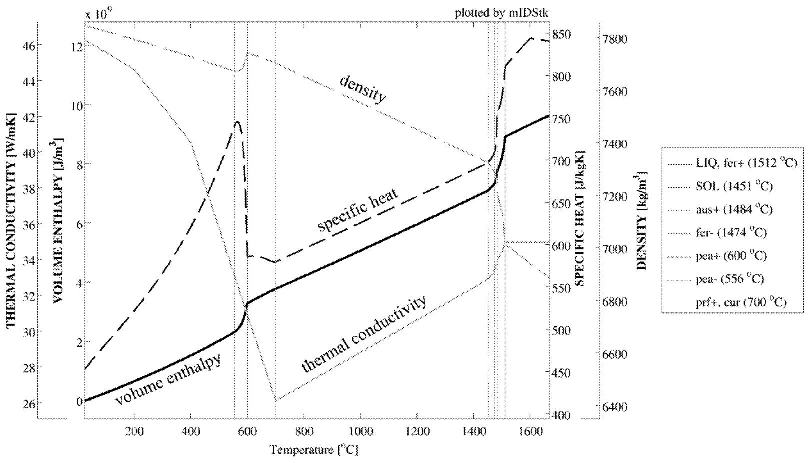

Fig.3: Dependency of thermophysical properties on temperature for steel grade S355J2G3

The dependency of the volume enthalpy, thermal conductivity, specific heat, and the density on the temperature obtained by using the solidification analysis package IDS for unalloyed fine-grained steel grade S335J2G3 and its chemical composition given in Tab. 1 is shown in Fig. 3. As can be seen, all the thermophysical properties significantly alter with the temperature, mainly in the temperature ranges of phase changes.

4. Analysis of thermal behaviour of cast steel billets and discussion

The thermal analysis was carried out for 200×200 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) is considered. When continuously casting in steelworks, casting temperatures of steel grades are usually not equal to each other (because of different melting temperatures, and of specific levels of overheating), and therefore the casting temperature was set to 1,555 °C for all steel grades in order to perform the comparable thermal analysis. The casting speed was set to 0.9 m/min for all steel grades.

The surface temperatures within the mould and the secondary cooling beneath the cooling nozzles and at the corner are shown in Fig. 4 and Fig. 5, respectively. Beneath the

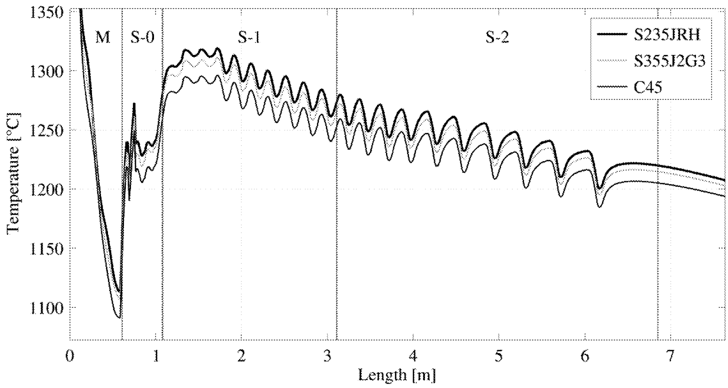

Fig.4: Top surface (small radius) temperatures beneath cooling nozzles within the mould and the secondary cooling

nozzles the surface temperature oscillates due to the effect of cooling nozzles and the heat withdrawal. 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 position of the length increases, the temperature fluctuations becomes larger due to the increasing distance of nozzles, see Fig. 4. In the mould the surface temperature beneath nozzles steeply decreases owing to the intensive heat withdrawal. Behind the mould the surface temperature precipitously increases with the temperature perturbation due to the influence of cooling nozzles (see the section S-0 in Fig. 4).

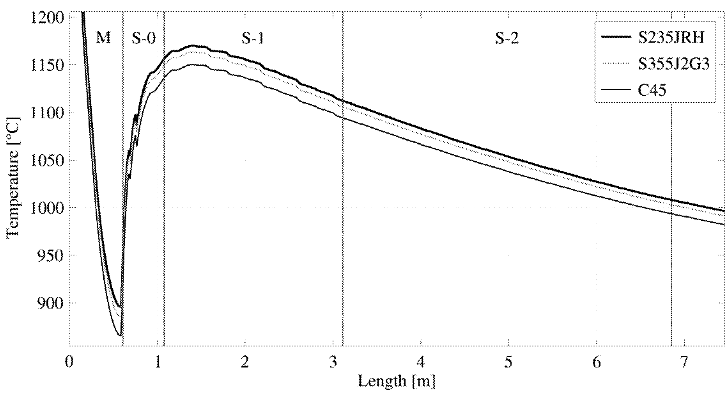

Fig.5: Corner temperatures (top surface – small radius) within the mould and the secondary cooling

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 the billet. Similarly to the case of the temperatures beneath nozzles, the steel grade C45 keeps the lowest temperatures in the corner whereas the steel grade S235JRH the highest ones, see Fig. 5. However, the difference between the corner temperatures of steel grades is only 8 °C. Analogously as in the case of surface temperatures, the corner temperature steeply decreases in the mould, and increases behind the mould but without the temperature perturbation because of no direct influence of the corner temperature on the cooling nozzles (see the section S-0 in Fig. 5).

The isosolidus and isoliquidus curves for all three steel grades are shown in Fig. 6. A significant influence of chemical composition to the isosolidus and isoliquidus curves, and thus to the metallurgical length can be observed [1]. The length of the isosolidus curve and thus the metallurgical length for the steel grade S235JRH is 13 m, but 13.65 m for S355J2G3 and even 14.3 m in the case of the steel grade C45. However, the isoliquidus curves of both the grades S355J2G3 and C45 are almost identical with the maximum length of 9.1 m (in the axis of the billet), but the maximum length of the isoliquidus curve of the grade S235JRH is even 10.65 m. Thus the steel grade C45 with 0.46 % of carbon results in the widest mushy zone whereas the grade S235JRH (0.07 % of carbon) to the narrowest one, see Fig. 6. It is worth pointing out that mainly the metallurgical length has to be prudently controlled in continuous casting, e.g., due to the straightening process, or due to the complete solidification and the consequent cutting of billets.

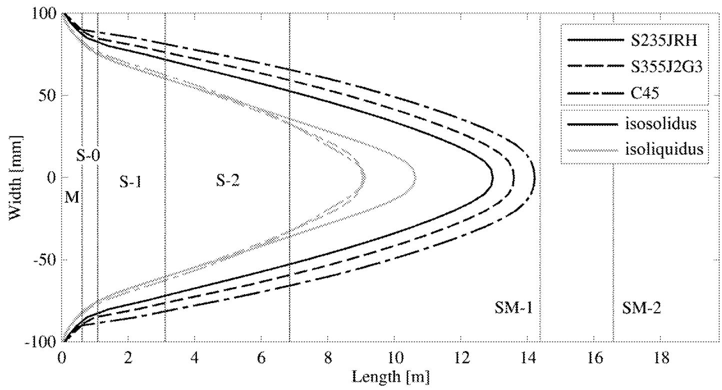

Fig.6: Isosolidus and isoliquidus curves

Another important parameter of continuous steel casting is the shell thickness growth along cast billets. It is fundamental to pay attention to the shell thickness, mainly behind the mould, in order to prevent billets from the rupture of the solid shell by the liquid melt due to ferrostatic pressure. The dependency of the shell growth on steel grade being cast is shown in Fig. 7. As can be observed, the shell thickness of steel grade S235JRH grows faster than the shell of S355J2G3, and mainly than the shell of steel grade C45 which needs the longest time to be solidified. The billets of the steel grade S253JRH is completely solidified (i.e., the shell thickness is 100 mm) in the length of 12.9 m where the shell thickness of S355J2G3 is 83 mm, and the thickness of C45 is only 72 mm. The billet of S355J2G3 is fully solidified in the length of 13.6 m but the shell thickness of C45 billet is only 79 mm, see Fig. 7.

The local periods of the solidification, which represent the width of mushy zone in the longitudinal direction related to the casting velocity, are shown in Fig. 8 where an interesting phenomenon during the solidification and in the thermal behaviour can be observed. In the case of the steel grade S355J2G3, the billet surface is solidified immediately inside the mould and the time needed to the solidification increases when approaching the core of billets. Nonetheless, the solidification process for the steel grades C45 and particularly for S235JRH behaves differently : the solidification takes the longest period in four positions outside the core of cast billets, see Fig. 8.

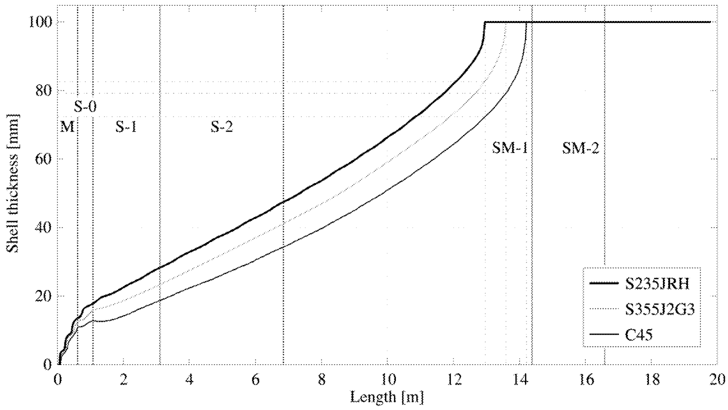

Fig.7: Shell thickness growth

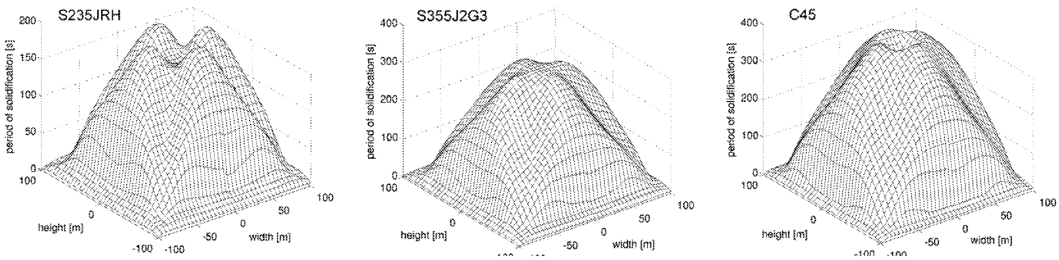

Fig.8: Local periods of solidification

5. Conclusion

The analysis of the thermal behaviour of continuously cast steel billets was performed by utilizing the original numerical model of the temperature field. Three steel grades with different carbon contents 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 a lower content of carbon tends to attain higher temperatures, both beneath nozzles and in corners, and with a narrower mushy zone. On the contrary, steel with a higher content of carbon reaches lower both surface and corner temperatures, and the mushy zone becomes wider. The analysis showed that a direct influence (temperature fluctuations along the billet) of used cooling nozzles on corner temperatures for the particular caster configuration is minor. The shell thickness is also dependent on the steel grade being cast and its chemical composition: the lower the carbon content the greater the shell thickness along the caster. Further, the particular chemical composition and the carbon content also have an influence on the local solidification period that can chiefly affect the structure of steel in the core of cast billets. It should also be pointed out that the analysis was carried out for the identical casting conditions (e.g., the casting temperature and cooling conditions in secondary cooling zone) for all three steel grades with different chemical compositions in order to obtain comparable results from the theoretical point of view. However, this is usually not the case in practice, and therefore the presented results are limited rather for theoretical analyses.

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