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COMPARISON OF THE TEMPERATURE FIELDS OF CONTINUOUSLY CAST STEEL SLABS WITH DIFFERENT CHEMICAL COMPOSITIONS

PRIMERJAVA TEMPERATURNEGA POLJA KONTINUIRNO ULITIH JEKLENIH SLABOV RAZLIČNIH KEMIJSKIH SESTAV

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The numerical model made by the authors was used for simulating the transient temperature fields of the continuously cast steel slabs with two different chemical compositions. The model solves the Fourier-Kirchhoff equation of the temperature fields of the slab-crystallizer system and the slab-ambient system with the following main thermophysical parameters: thermal conductivity, specific-heat capacity, density and enthalpy. When both melts follow each other closely, the critical state of the so-called breakout occurs at a certain point in the secondary cooling zone of a caster. It is probably a combination of surface defects. However, different chemical compositions of the two steels and their mixture are apparently decisive. Therefore, the temperature model simulated the temperature history of every point of a cross-section of a slab during its movement through the caster from the level of the melt in the crystallizer to the cutting torch for both melts and their mixture. The calculation of the temperature field of a slab is mainly focused on the part of the slab before the breakout and its surroundings. The results for the temperature field are used to set up a model of chemical heterogeneity of the steel supported by the material investigation of the samples taken from the breakout.

Keywords: continuously cast slab, temperature field, chemical composition, heterogeneity, numerical model, breakout

Uporabljen je bil originalen numerični model za simulacijo prehodnega temperaturnega polja kontinuirno ulitih jeklenih slabov dveh različnih kemijskih sestav. Model rešuje Fourier-Kirchhoffovo enačbo za sistema slab-kristalizator oz. slab-okolje z naslednjimi glavnimi termo-fizikalnimi parametri: toplotna prevodnost, specifična toplotna kapaciteta, gostota in entalpija. Ko se talina v formi zmeša s prejšnjo, pride do kritičnega stanja, t. i. prodora v določeni točki livne sekundarne hladilne cone. To nastane verjetno zaradi kombinacije površinskih napak. Tako je različna kemijska sestava dveh jekel in njihovo mešanje očitno odločilno pri tem pojavu. Temperaturni model je simuliral temperaturni potek v vsaki točki prečnega prereza slaba med njegovim gibanjem skozi celotni livni stroj od nivoja taline v kristalizatorju do rezalnega plamena za obe talini in njune mešanice. Izračun temperaturnega polja slaba je bil osredinjen predvsem na del slaba pred prodorom in njegovo okolico. Model kemijske heterogenosti jekla se lahko uveljavi z rezultati temperaturnega polja in z raziskavami vzorcev, ki so bili odvzeti iz območja prodora.

Ključne besede: kontinuirno ulit slab, temperaturno polje, kemijska sestava, heterogenost, numerični model, prodor

1 INTRODUCTION

The authors continue the study of the causes for the breakouts of continuously cast steel slabs of 250 mm × 1530 mm covered in the previous publications.[1–3] This is a defect that cannot be repaired. The break was detected in the unbending point of a slab, at a distance of 14.15 m away from the level of the melt inside the mould, where a breakout occurred between the 7th and 8th cooling segments of the secondary cooling zone. The difference in the heights between the level inside the mould and the breakout point was 8605 m. This tear in the shell occurred on the small radius of the caster. Here, the slab is beginning to straighten out and the breakout of the steel can occur in the points of the increased local chemical and temperature heterogeneities of the steel. The changes in the chemical composition of the steel during the actual continuous casting are especially dangerous. This change in the chemical composition of the steel of two qualities, A and B, was carried out very quickly, by changing the tundish. Inside the mould, steel B mixed with steel A of the previous melt. Therefore, the results of the calculation of the temperature fields of the slabs with the chemical compositions A, B and of the mixed composition A + B will be presented. The mixed content of each element is considered as the average value of the composition A and B.

2 3D NUMERICAL MODEL OF THE TEMPERATURE FIELD OF A STEEL SLAB AND PREPARATION FOR THE SIMULATION

The optimisation of the production on casters, with the aim of achieving the maximum savings and maximum quality of the product is unthinkable without the knowledge of the course of the solidification and cooling of the concasting. The solidification and cooling of a concast slab is a global problem of the 3D transient heat and mass transfer. If the heat conduction within the heat transfer in this system is decisive, the process is described with the Fourier-Kirchhoff equation. It describes the temperature field of the solidifying slab in all three of its states: at the temperatures above the liquidus (i.e., the melt), within the interval between the liquidus and solidus (i.e., in the mushy zone) and at the temperatures below the solidus (i.e., the solid state). In order to obtain these results, it is convenient to use the explicit numerical method of finite differences. A numerical simulation of the release of latent heats of the phase or structural changes is carried out by introducing the enthalpy function dependent on temperature *T*. The latent heats are expressed after an automated generation of the network (pre-processing) ties on the entry of the thermophysical material properties of the investigated system. They are the heat conductivity *k*, the specific heat capacity *c* and the density ρ of the cast metal.

The temperature distribution in the slabs described with the enthalpy balance equation is as follows:

$$\begin{aligned}&\frac{\partial(\rho H)}{\partial t}+\frac{\partial}{\partial x}(\rho u H)+\frac{\partial}{\partial y}(\rho v H)+\frac{\partial}{\partial z}(\rho w H)=\\&=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)\end{aligned} \tag{1}$$

The simplified equation (1), suitable for an application on the radial casters with a great radius, where only the speed (of the movement of the slab) component *w* in the *z*-direction is considered, is:

$$\begin{aligned}&\frac{\partial(\rho H)}{\partial t}+\frac{\partial}{\partial z}(\rho w H)=\\&=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)\end{aligned} \tag{2}$$

The unknown enthalpy of the general nodal point of a slab in the next time step ($t+\Delta t$): $H_{i,j,k}^{(t+\Delta t)}$ is expressed with the explicit formula and it is a function of the enthalpies of the same node and six adjacent nodes in the Cartesian coordinate system from the previous time step *t*.

The thermophysical properties of the cast materials, *k, c* and ρ, contained in the equation and dependent on the chemical compositions are also functions of the temperature.[4] The function of enthalpy *H* is not known as an analytical function, but as a set of tabular values, which means that a reverse determination of the temperature is numerically a highly demanding task. It is also dependent on the composition of the steel and on the rate of cooling.

Figure 1 shows that the task is symmetrical along the x-axis; it is, therefore, sufficient to investigate only one half of the cross-section. The 3D model was first designed as an off-line version and later as an on-line version so that it could work in real time. After the correction and testing, it will be possible to implement it on any caster thanks to the universal nature of the code. The numerical model takes into account the temperature field of the entire slab (from the meniscus of the level of the melt in the mould to the cutting torch) with the number of the nodes exceeding 10^6 on the half of the cross-section of the rectangular profile. The solution is performed under these boundary conditions:

$$T=T_{\text{cast}} \text{ at the meniscus} \tag{3a}$$

$$-k\frac{\partial T}{\partial n}=0 \text{ at the plane of symmetry} \tag{3b}$$

$$-k\frac{\partial T}{\partial n}=h(T_{\text{surf}}-T_{\text{mould}}) \text{ in the mould} \tag{3c}$$

$$-k\frac{\partial T}{\partial n}=h(T_{\text{surf}}-T_{\text{amb}})+se(T_{\text{surf}}^{4}-T_{\text{amb}}^{4}) \tag{3d}$$

in the secondary and tertiary cooling zones

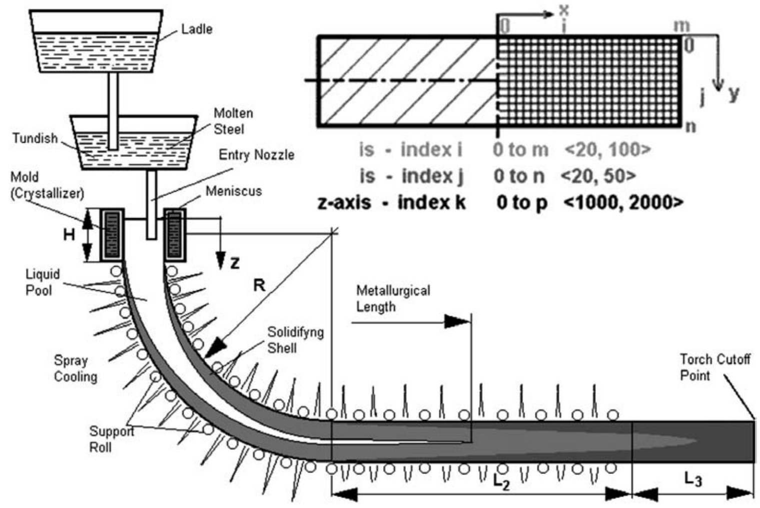

Figure 1: Caster and definition of the coordinate system
Slika 1: Livni stroj in definicija koordinatnega sistema

$$-k\frac{\partial T}{\partial n}=q \text{ beneath the support rollers} \qquad (3e)$$

The initial condition for obtaining a solution is the setting of the initial temperature in individual points of the network. The suitable value is the highest possible temperature, i.e., the casting temperature T_{cast}.

It is, therefore, a solution of a distinctly non-linear task, since even for the boundary conditions their dependence on the surface temperature of a continuously cast slab is respected. All the boundary conditions were derived and were then divided to the areas of the mold (the primary cooling) and of the secondary and tertiary cooling. The zero heat flow perpendicular to the symmetry plane is the boundary condition that is common to all the zones of the caster.[5]

In equations (1–3) T is the temperature in K, t is the time in s, k is the heat conductivity in W m^{-1} K^{-1}, ρ is the density in kg m^{-3}, x, y, z are the axes in the given directions in m, u, v, w are the velocities in the given directions (the shift rate) in m s^{-1}, H is the specific enthalpy in J kg^{-1}, T_{surf}, T_{amb} are the surface and ambient temperatures in K, T_{cast}, T_{mould} are the casting and the mould temperatures in K, σ is the Stefan-Boltzmann constant (5.76×10^{-6} W m^{-2} K^{-4}), ε is the emissivity (0.8), n is normal to the surface in m, h in W m^{-2} K^{-1} is the heat-transfer coefficient (HTC), q in W m^{-2} is the specific heat flow.

The heat-transfer coefficient h is a function of the local cooling rate and the surface temperature, the temperature T_{amb} is the cooling-water temperature in the secondary-cooling zone and the air temperature, where only radiation occurs. Based on the results of the previous investigations, the boundary conditions are set identically within each zone individually. The definition of the boundary conditions under the cooling jet is especially difficult. In order for the model to function correctly, it is necessary to determine the correct value of the heat-transfer coefficient h underneath the jet. Therefore, extensive experiments were conducted on a laboratory device simulating the process of solidification within the secondary-cooling zone. These measurements were conducted for various operation conditions, i.e., the pressure of the water and the shift rate. The numerical model contains a function that calculates the current on the basis of the entered water pressure, the shift rate, the positions of the jet and the surface temperature.

The casting speed was 0.0130 m s^{-1} (steel A) and 0.0126 m s^{-1} (steel B), the superheat was 23 °C (steel A) and 18 °C (steel B), the solidus temperature was 1427.0 °C (steel A) and 1480.6 °C (steel B), the liquidus temperature was 1493.9 °C (steel A) and 1512.3 °C (steel B).

The chemical composition of steel A in mass fractions (%) was: w(C) = 0.416, w(Cr) = 0.95, w(Ni) = 0.03, w(Mn) = 0.7, w(Mo) = 0.206, w(Si) = 0.28.

The chemical composition of steel B in mass fractions (%) was: w(C) = 0.174, w(Cr) = 0.07, w(Ni) = 0.02, w(Mn) = 1.46, w(Mo) = 0.005, w(Si) = 0.23.

The thermophysical properties of the steels were calculated using the IDS solidification analysis package of a prestigious laboratory (the Laboratory of Metallurgy, Helsinki University of Technology). The IDS package calculates enthalpy, specific heat, density, thermal conductivity, thermal contraction, etc., from the liquid state down to the room temperature using graphic or numeric outputs of the results. The dependences of the main

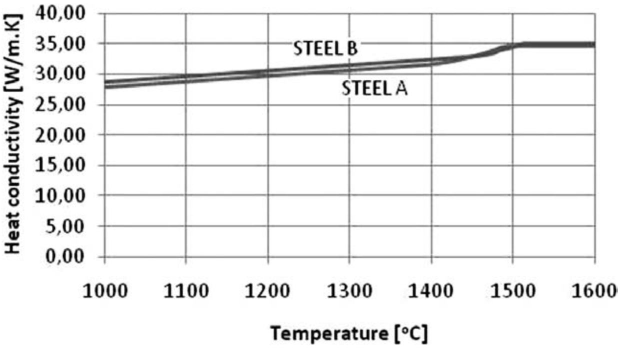

Figure 2: Heat conductivity of steels A and B and its dependence on temperature
Slika 2: Toplotna prevodnost jekel A in B v odvisnosti od temperature

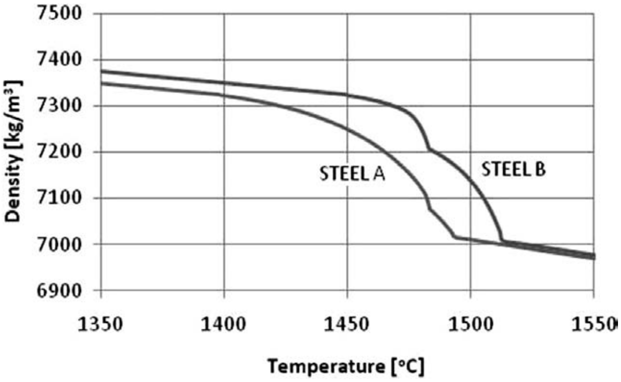

Figure 3: Density of steels A and B and its dependence on temperature
Slika 3: Gostota jekel A in B v odvisnosti od temperature

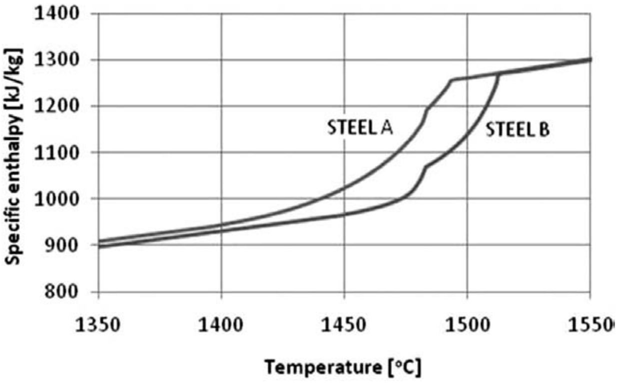

Figure 4: Enthalpy of steels A and B and its dependence on temperature
Slika 4: Entalpija jekel A in B v odvisnosti od temperature

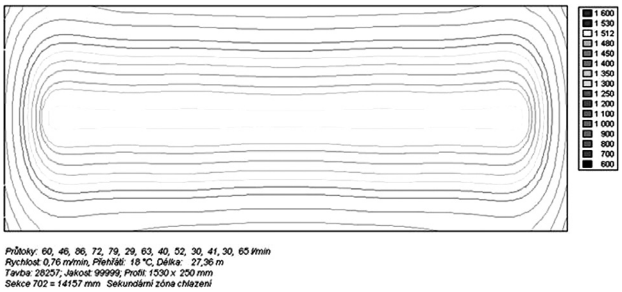

Figure 5: Isotherms in the cross-section of the breakout for the steel slab of B quality

Slika 5: Izoterme v prečnem prerezu prodora jeklenega slaba B

thermophysical properties on the temperature – the heat conductivity, the density and the enthalpy of both steels are shown in **Figures 2** to **4**. The definitions of the boundary conditions for all three variants of the calculation were identical for all the cooling zones.

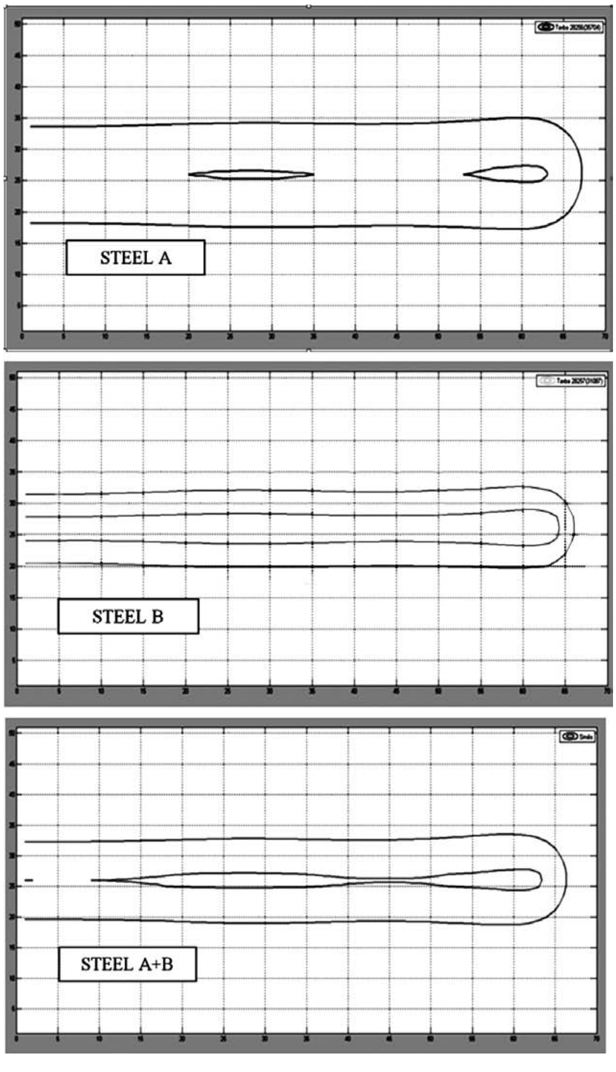

Figure 6: Isoliquidi and isosolidi in the cross-section of the breakout for the steel slabs of A, B and A + B qualities

Slika 6: Izolikvidusne in izosolidusne črte v prečnem prerezu prodora za jekli A in B ter za A + B

3 NUMERICAL RESULTS

The off-line version of the original temperature model was now used to simulate the temperature fields of the steel slab of A quality, the steel slab of B quality and the steel slab of A + B quality (with the average chemical compositions). After the computation, it is possible to obtain the temperatures for each node of the network and for any time during the process. The course of the calculated isotherms in the cross-section of the breakout, for example, for a slab of B quality at a distance of 14.15 m from the level of the melt in the mold is in **Figure 5**.

The courses of the calculated isoliquidi and isosolidi as the characteristic isotherms in one half of the cross-section of the breakout for the steel slabs of A, B and A + B qualities are in **Figure 6**. The isoliquidi and isosolidi in both longitudinal axial sections of the steel slabs of A, B and A + B qualities are plotted in **Figures 7** and **8**.

4 CONCLUSIONS

In the secondary-cooling zone, where the slab is beginning to straighten out, the breakout of the steel can occur in the points of increased local chemical and temperature heterogeneities of the steel, from the increased

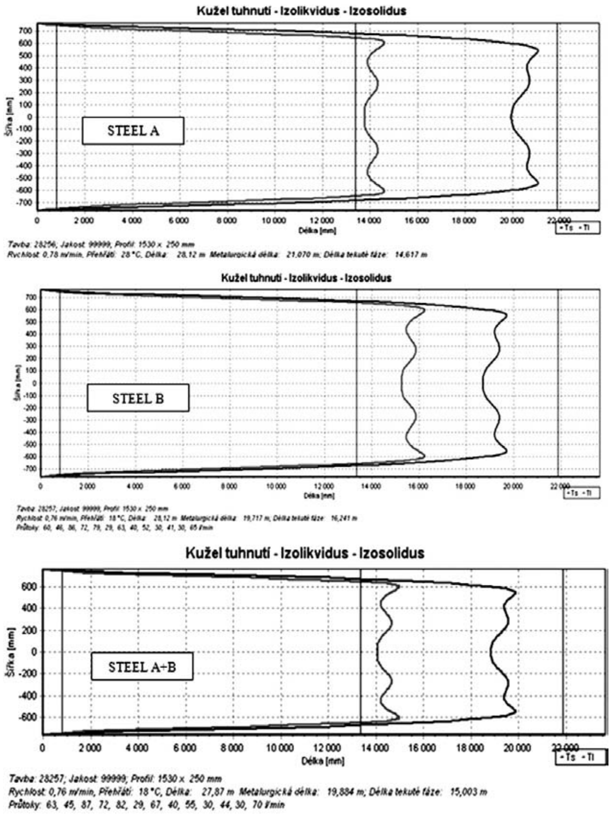

Figure 7: Isoliquidi and isosolidi in the horizontal section for the steel slabs of A, B and A + B qualities

Slika 7: Izolikvidusne in izosolidusne črte v horizontalnem prerezu za jekli A in B ter za A + B

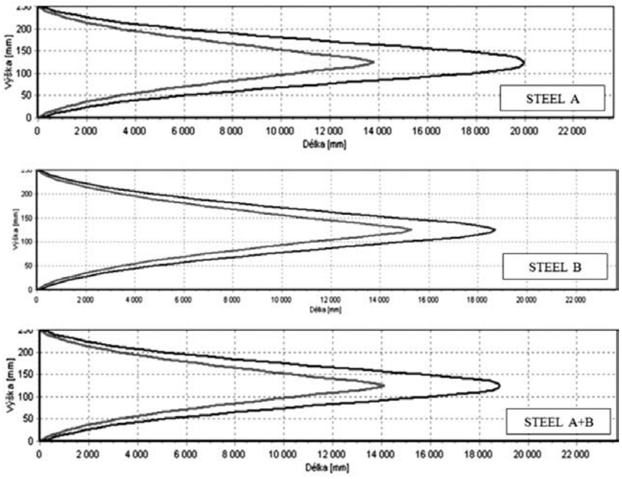

Figure 8: Isoliquidi and isosolidi in the vertical-axis section for the steel slabs of A, B and A + B qualities

Slika 8: Izolikvidusne in izosolidusne črte v vertikalnem osnem prerezu za jekli A in B ter za A + B

tension as a result of the bending of the slab and also a high local concentration of non-metal, slag inclusions. The changes in the chemical composition of the steel during the fill-up of the tundish with continuous casting are especially dangerous. The consequence of this operation, an immediate change in the chemical composition of the steel, which is not prevented by a breakout system directly inside the mould, can lead to an immediate interruption of the concasting and a breakout at a greater distance from the mould than usual, thus leading to a significant material loss and downtime.

During the continuous casting of the slab of 250 mm × 1530 mm and after a quick change of the tundish, a change in the chemical composition of steel A and B occurred. Inside the mould, steel B thus mixed with steel A of the previous melt. After 20 min of casting steel B with a different chemical composition, the caster stopped as a result of a breakout at a distance of 14.15 m from the level of the melt in the mold. Therefore, this critical state of continuous casting was analyzed via the temperature model that may be followed by an analysis of the chemical heterogeneity in the plain of the breakout. The results of the formation of the temperature fields of the steel slabs of quality A, B, and A + B (with the average chemical compositions) were obtained. The objective of the paper is to analyse the temperature fields in the plain of the breakout, which may be followed by an analysis of chemical heterogeneities in this plain. In the case of a breakout we do not have more detailed information about the internal relationship between the dimensional quantities and the essence of the breakout, and we do not even have a partial mathematical and physical description of this phenomenon. That is why it is necessary to use the theory of similarity for a dimensional analysis determining the dimensionless criteria.[6] Based on the π-theorem, 5 similarity criteria were derived containing 12 technological, geometrical and thermo-physical dimensional quantities that characterise both steel grades A and B and also the process of their continuous casting. This analysis also provides the calculations of the temperature fields of the slabs to be cast, in order to determine the quantities needed for the fulfilment of some of these criteria. The analysis performed by using the similarity criteria clearly demonstrates a significantly increased tendency for steel B to breakout, in comparison with steel A.

Acknowledgment

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