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RESEARCH OF THERMAL PROCESSES FOR THE CONTINUOUS CASTING OF STEEL

RAZISKAVE TERMIČNIH DOGAJANJ PRI KONTINUIRNEM ULIVANJU JEKLA

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The article deals with the determination of the basic indicators of heat transfer in the continuous casting of steel, which can be described as an unsteady process with complicated boundary conditions for the solution. An analytical solution of this problem is practically impossible and, therefore, mathematical modelling is applied with a certain simplification of the real conditions and with a description of those criteria that influence the most the process of solidification and cooling. Using a simulation program and the knowledge of input parameters, it was possible to predict the distribution of the thermal field of a continuously cast blank in the course of its casting. Simulations also allowed us to deal with the issues of the inner structure, surface quality, mechanical properties of a continuously cast blank, metallurgical length, change in the thickness of a strand shell and overheating of steel. Some results obtained with numerical simulations are documented for concrete examples.

Keywords: continuous casting of steel, modelling, heat transfer, shell, mould

Članek obravnava določanje osnovnih pokazateljev prenosa toplote pri kontinuirnem ulivanju jekla, ki se lahko opišejo kot nestabilen proces s kompliciranimi robnimi pogoji za rešitev. Analitska rešitev tega problema je praktično nemogoča, zato je bilo uporabljeno matematično modeliranje z nekaterimi poenostavitvami realnih pogojev in z opisom tistih meril, ki najbolj vplivajo na proces strjevanja in ohlajanja. S programom za simulacijo in poznanjem vhodnih parametrov je bilo mogoče predvideti razporeditev temperaturnega polja kontinuirno ulite gredice med njenim ulivanjem. Uporaba simulacije je omogočila opis notranje strukture, kvalitete površine, mehanskih lastnosti kontinuirno ulite gredice, metalurške dolžine, spreminjanja debeline strjene skorje in pregretja jekla. Nekateri rezultati, dobljeni z numerično simulacijo, so prikazani za konkretne primere.

Ključne besede: kontinuirno ulivanje jekla, modeliranje, prenos toplote, skorja, kokila

1 INTRODUCTION

Mathematical precise description of thermal processes during the continuous casting of steel is very difficult, since the process of cooling and solidification of a continuously cast blank is influenced by many factors.

For this reason it is necessary to find, with the help of mathematical and physical modelling, the criteria that have the biggest influence on the solidification and cooling of a continuously cast blank. Understanding the thermal processes taking place during the continuous casting of steel is of crucial importance because it enables a prediction of a formation of defects, an enhancement of the thermal processes during continuous casting, the optimum locations for cooling nozzles or a minimisation of breakout risks, etc.[1]

It is evident, that it is impossible to optimise the process of continuous casting of steel only by modelling. A very close interaction with the results of experimental measurements is always necessary since these results introduce, into the system, characteristic features of a concrete continuous-casting machine. At present, it is possible to perform, with the use of sophisticated software, not only the thermal calculations but also the calculations of stress conditions, and also to predict segregation during the continuous casting of steel. The finite-element method or finite-difference method are used most frequently as the calculation algorithm in this software.

This paper deals with the solution of thermal processes during the continuous casting of round steel blanks with a diameter of 410 mm, using the simulation software based on the explicit finite-element method.

2 THERMAL FIELD OF A CONTINUOUSLY CAST BLANK

The kinetics of an unsteady thermal field is described with the Fourier partial differential equation.[2] If we want to describe the thermal field of a moving, continuously cast blank, it is necessary to take into account, in the transverse direction, also the rate of casting, by transforming the classical Fourier equation to the Fourier-Kirchhoff equation:

$$\frac{\partial t}{\partial \tau} = a \cdot \nabla^2 t + \frac{q_v}{c_p \cdot \rho} \quad (1)$$

where a/(m^2/s) is the temperature-conductivity coefficient, ∇^2/(m^{-2}) is the Laplace's operator, c_p/(J/kg K) is the specific heat capacity, ρ/(kg/m^3) is the density and q_V/(W/m^3) is the inner heat source.

This equation can only be solved with the conditions of monovalency of the solution, which, in the classical concept, are divided into geometric, physical, surface and initial conditions. Physical conditions are generally created with the chemical composition of the cast steel, geometric conditions are created with the shape of the cast products, and the initial condition is closely linked to the temperature of the liquid steel in a tundish. Numerous researches concerning the continuous casting of steel[3–6] combined with modelling physical models use the Neumann surface condition for the mould and the Fourier condition for the secondary and tertiary cooling.

3 SIMULATION MODELLING

For numerical modelling, the ProCAST program tool was used, which is based on the implicit finite element method. Alternatively, an original program code Tefis based on the explicit finite difference method, specially designed for numerical modelling of the continuously cast blank temperature field, was used. The program Tefis enables real-time simulations too. The second method requires compliance with a numeric stability condition, which describes mutual dependence between fineness of the calculation mesh and calculation time step.

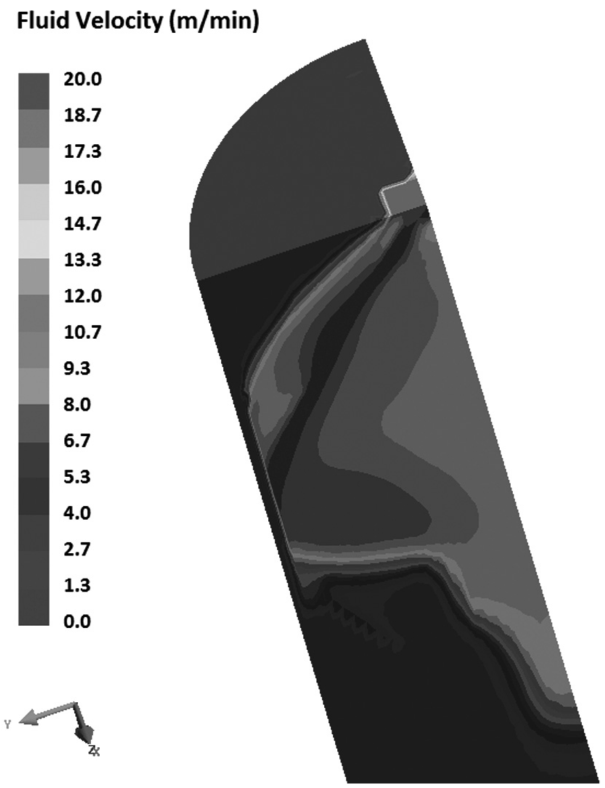

Figure 1: Velocity vectors of a blank
Slika 1: Vektor hitrosti v gredici

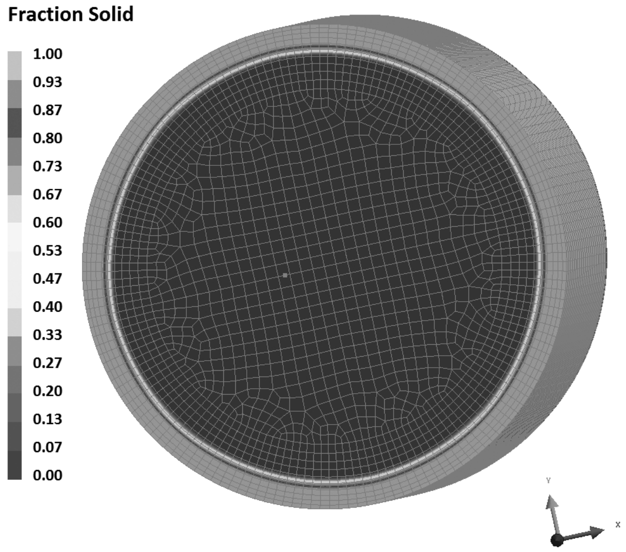

Figure 2: Calculation mesh of a blank
Slika 2: Računska mreža gredice

An application of program ProCAST consists of five modules, which are functionally mutually interconnected. The first module is used for defining the body geometry and for selecting the fineness and the shape of the calculation mesh. It is then necessary to determine the physical, initial and surface conditions that may be modified in line with the requirements of the next module. After correctly entering the initial calculation parameters, the main calculation module of the software launches the program.

The program allows a graphical visualisation of the calculated results and an export of the values, graphs and images for further processing. The program can launch a calculation in two modes – the thermal and flow modes. The results of the thermal mode give the thermal fields of a round, continuously cast blank without the velocity vectors of liquid steel. If it is also required to visualise the velocity vectors, then it is necessary to activate the flow mode (**Figure 1**).

Distribution of the temperatures during the solidification or cooling is calculated in the nodal points of the whole volume of a continuously cast blank (**Figure 2**).

The program also comprises a vast database of the information about cast steel grades, including their thermophysical properties (density, specific heat capacity, heat conductivity, viscosity, etc.).

4 RESULTS OF NUMERICAL SIMULATIONS

Within the research two steel grades of different chemical compositions used for the production of continuously cast blanks with a diameter of 410 mm were subjected to a simulation (**Table 1**). The following influences were analysed: the influence of the chemical composition, the casting rate, overheating of the steel above the liquidus temperature, the influence of the molten-steel level in the mould on the resulting technological parameters, generally represented with the metallurgical length, the length of the liquid phase, the surface temperatures of a continuously cast blank at the outlets of the primary and secondary cooling zones, and the thickness of the strand shell.

Table 1: Chemical composition of the steel in mass fractions, *w*/%
Tabela 1: Kemijska sestava jekla v masnih deležih, *w*/%

Brand of the steel	Chemical composition, *w*/%				
	C	Mn	Si	P	S
Steel A	0.168	1.350	0.381	0.013	0.007
Steel B	0.913	0.342	0.246	0.009	0.004

The chemical compositions, especially the carbon contents, have a principal influence on the heat removal in all the zones of the continuous-casting machine. In the case of low-carbon steels the biggest shrinkage of the strand shell occurs as a result of a peritectic reaction as well as a considerable deceleration of its growth, which is manifested by a reduction of the heat-flow density through the mould wall to its minimum. Another result of this reaction is an increased occurrence of surface defects of a continuously cast blank, particularly of surface cracks.

The casting rate is related to the dimensions of a continuously cast blank, the type of steel and the type of mould. Higher values of the casting rate cause a shorter stay of a continuously cast blank in the mould, which increases the surface temperatures and, simultaneously, also the local values of the thermal-flow density.

It may be stated on the basis of the performed simulations that, with respect to investigating the influence of the casting rate on the metallurgical length and the length of the liquid phase, their very strong linear dependence is evident and is best characterised with a high value of the slope in the regression equations (**Figure 3**).

The growth of the strand shell with the changing casting rate (**Figure 4**) confirms the previous scientific research works,[7,8] which document the fact that the para-

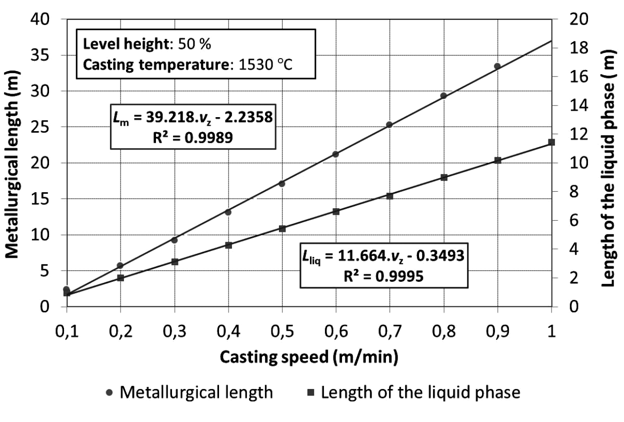

Figure 3: Influence of the metallurgical length depending on the casting speed in the case of steel A
Slika 3: Vpliv metalurške dolžine v odvisnosti od hitrosti litja v primeru jekla A

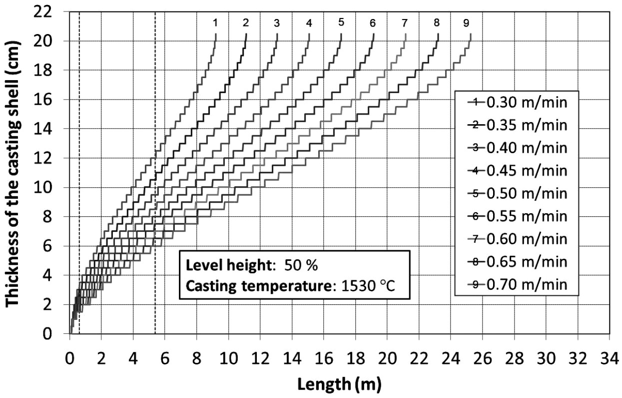

Figure 4: Increase in the thickness of the casting shell depending on the casting speed in the case of steel A
Slika 4: Povečanje debeline skorje, v odvisnosti od hitrosti litja v primeru jekla A

bolic law may be used for the solidification of an ingot to a distance of approximately 75 % of the diameter of a continuously cast blank from the ingot mould surface. When this critical value is exceeded, the differences are more pronounced, as it is known that the solidification of round, continuously cast blanks accelerates towards their centre, in comparison to the ingot mould.

The thickness of the shell can determine the results of the logarithmic equation for steel A:

$$\xi = (-1.490 \cdot 10^{-2} \cdot \ln v_z + 1.683 \cdot 10^{-1}) \cdot \tau^{(-6.378 \cdot 10^{-3} \cdot \ln v_z + 5.874 \cdot 10^{-1})} \tag{2}$$

And for steel B, the following applies:

$$\xi = (-1.3690 \cdot 10^{-2} \cdot \ln v_z + 1.869 \cdot 10^{-1}) \cdot \tau^{(-9.369 \cdot 10^{-3} \cdot \ln v_z + 5.456 \cdot 10^{-1})} \tag{3}$$

where v_z/(m/s) is the specific casting rate and τ/s is the casting time.

Finally, an analysis of the influence of overheating of steel on the investigated technological parameters was made. Overheating of steel can be defined as the difference between the casting temperature and the liquidus

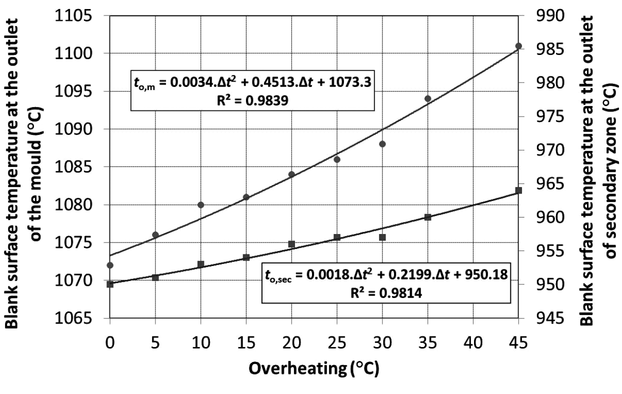

Figure 5: Blank-temperature change depending on the overheating of steel B
Slika 5: Sprememba temperature gredice glede na pregrevanje jekla B

temperature. This temperature difference should be, from the viewpoint of the operation, as small as possible, since it reduces the thermal stress and the energy intensity of the continuous casting of steel, as well as the scrap factor and the formation of surface cracks (**Figure 5**).

The results of the simulations also show that the greater is the overheating of steel, the later is the solidification of a continuously cast blank and the greater is the distance of this solidification from the molten-steel level. The overheating of steel in the interval from 0 °C to 45 °C increases the metallurgical length, on average, by 0.5 m, and a similar trend is characteristic of all steel grades. Even a greater influence of this parameter on the increase in the length of the liquid phase was confirmed. An increase in the overheating temperature by 40 °C above the liquidus temperature caused an elongation of the metallurgical length, on average by 3 %; however, the length of the liquid phase was increased even by 20 %, while the surface temperature of a continuously cast blank at the output from the primary and secondary cooling zones increased by up to 3 %.

5 CONCLUSION

The optimum configuration of the thermal mode of the continuous casting machine substantially influences the quality of the cast products. The processes participating in the cooling and solidification of a continuously cast blank show their physical characters in the complicated transfer phenomena of the heat and mass transfer. In order to allow a general solvability of these tasks, computer simulations are used making it possible to define the optimum parameters of the continuous casting of steel. The casting rate, which influences practically all the casting parameters, appeared to be most important quantity.

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