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OPTIMIZATION OF THE QUALITY OF CONTINUOUSLY CAST STEEL SLABS USING THE FIREFLY ALGORITHM

OPTIMIZACIJA KAKOVOSTI KONTINUIRNO LITE JEKLENE PLOŠČE Z UPORABO ALGORITMA "FIREFLY"

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The ambition to increase both the productivity and the product quality in the continuous casting process, led us to study new, effective mathematical approaches. The quality of the steel produced with the continuous casting process is influenced by the controlled factors, such as the casting speed or cooling rates. The appropriate setting of these factors is usually obtained with expert estimates and expensive experimental runs. This paper describes an algorithm for obtaining a black-box-type solution which maintains a high production rate and the high quality of the products. The core of the algorithm is our original numerical model of 2D temperature field designed for the real caster geometry. The mathematical model contains Fourier-Kirchhoff equation and includes boundary conditions. Phase and structural changes are modeled by the enthalpy computed from the chemical composition of the steel. The optimization part is performed with a recently created heuristic method, the so-called Firefly algorithm, in which the principles of searching for optimal values are inspired by the biological behavior of fireflies. Combining the numerical model and heuristic optimization we are able to set the controlled values and to obtain high-quality steel that satisfies the constraints for the prescribed metallurgical length, core and surface temperatures. This approach can be easily utilized for an arbitrary class of steel only by changing its chemical composition in the numerical model. The results of the simulations can be validated with real historical data in order to compare the relationship between the temperature field and the final product quality.

Key Words: continuous casting, Firefly algorithm, temperature field, enthalpy approach

Ambicije za povečanje produktivnosti in kakovosti končnega proizvoda pri kontinuirnem ulivanju sta nas pripeljala do študija novih učinkovitih matematičnih prijemov. Na kakovost jekla, proizvedenega s kontinuirnim ulivanjem, vplivajo številni nadzorovani dejavniki, kot sta npr. hitrost ulivanja in ohlajanja. Ustrezno določanje teh dejavnikov je navadno povezano s strokovnimi ocenami in dragimi poizkusi. Prispevek opisuje algoritem za vrsto rešitev za ohranjanje visoke stopnje proizvodnje in visoke kakovosti izdelkov. Jedro algoritma je naš prvotni numerični model 2D-polja temperature, namenjen ulivalni geometriji. Ta matematični model vsebuje Fourier-Kirchhoffovo enačbo in tudi robne pogoje. Fazne in strukturne spremembe so bile modelirane z entalpijo, izračunano iz kemijske sestave jekla. Optimizacijski del je bil izveden z nedavno narejeno hevristično metodo, s tako imenovanim algoritmom Firefly, kjer načela iskanja optimalnih vrednosti temeljijo na biološkem vedenju kresnic. Z združevanjem numeričnega modela in hevristične optimizacijo smo lahko predpisali nadzorovane vrednosti za izdelavo visokokakovostnega jekla, ki izpolnjuje predpisane pogoje za zagotovitev metalurške dolžine, ter temperature jedra in površine. Ta način je mogoče enostavno uporabiti za katero koli vrsto jekla le s spremembo kemične sestave v numeričnem modelu. Rezultate simulacij lahko potrdimo z resničnimi podatki iz preteklosti s primerjavo razmerja med temperaturnim poljem in kakovostjo končnega izdelka.

Ključne besede: kontinuirno litje, entalpija, algoritem Firefly, temperaturno polje

1 INTRODUCTION

Nowadays, continuous casting is the most common way of producing steel in the world. Every year, the steel industry processes millions of tons of liquid steel into semi-finished products such as slabs, blooms, and billets. A schematic representation of the continuous caster is shown in **Figure 1**. Molten steel (roughly 1550 °C) is poured down from a tundish into a water-cooled mould (primary cooling zone), where the steel obtains a solid shell. Afterwards, the steel is transported by rollers and cooled down by water sprays (secondary cooling zone). Groups of nozzles of sprays divide the secondary cooling zone into several coolant circuits. In the last zone, the steel surface is cooled down by free convection and radiation only (tertiary cooling zone).

Every steel company wants to produce steel as quickly as possible, while preserving the required

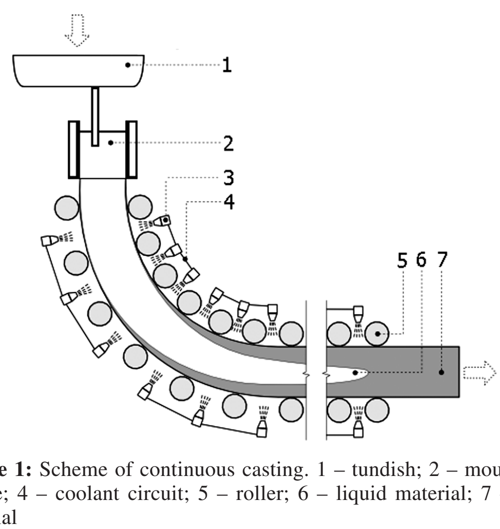

Figure 1: Scheme of continuous casting. 1 – tundish; 2 – mould; 3 – nozzle; 4 – coolant circuit; 5 – roller; 6 – liquid material; 7 – solid material

Slika 1: Shema kontinuirnega litja: 1 – vmesna ponova; 2 – kokila, 3 – šobe; 4 – hladilne šobe, 5 – valj, 6 – tekoči koren; 7 – trdna snov quality[1]. There are a few ways to optimize the casting velocity and the output quality simultaneously. One possible method is to perform industrial trials, but this is very expensive and time-consuming. A better way is to use numerical simulations of the casting process and adjust these parameters to the optimal values. Previous studies were generally based on a simplified 2D temperature field model and were optimized by mathematical programming[6], neural networks or a genetic algorithm.[2] These models describe the casting process very roughly and, therefore, their usage in real casters is not satisfactory.

Our original numerical model of the temperature field is designed for the real caster geometry. A modern heuristic method called the Firefly algorithm is used for the optimization of the model.

2 DEFINITION OF THE PROBLEM

The goal of the optimization is to improve the material properties of the final slab and increase the rate of production. With the aim to achieve this goal, we modified the casting process by controlling the casting speed and the cooling rates. The productivity is defined as the amount of cast material per unit time, thus, we maximize the casting speed under certain metallurgical criteria. The metallurgical criteria used in the optimization are formulated as a series of constraints that represent the quality of the slab products and the process feasibility. The criteria that must be met are the completeness of solidification before the unbending point (metallurgical length) and reaching the prescribed temperature in the exit area. The quality of the final material is influenced by the change of the surfaces and the core temperatures. The changes have to decrease in the whole profile and the temperature in the straightening area must be in the given range. The values for these constraints depend on the grade of cast steel.

3 MATHEMATICAL MODEL OF THE TEMPERATURE FIELD

All three basic mechanisms of heat transfer are incorporated into our model in a differential form. The conduction mechanism plays the dominant role inside the body of the cast steel, whereas convection and radiation take place only in the secondary and tertiary cooling zones, where they form the boundary conditions. The temperature field of the slab is described by the Fourier-Kirchhoff equation,[3,4] where the velocity component v_y/(m/s) is considered only in the direction of casting. Phase and structural changes are included in the model by the use of a thermo-dynamical function of the volume enthalpy H/(J/m^3). The method is also called an enthalpy approach.[3]

$$\frac{\partial H}{\partial \tau} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + v_y\frac{\partial H}{\partial y} \quad (1)$$

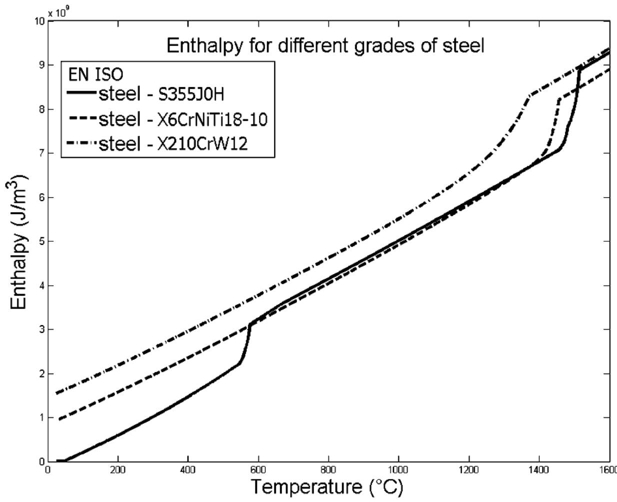

Figure 2: Relationship between the temperature and the enthalpy for three grades of steel
Slika 2: Razmerje med temperaturo in entalpijo za tri različna jekla

Equation (1) describes an unsteady-state 2D heat transfer (Fourier-Kirchhoff) written in Cartesian coordinates, where k/(W/mK) is the thermal conductivity, T/K is the temperature, H/(J/m^3) is the volume enthalpy, τ/s is the real time, and x, y, are space coordinates. In order to have a well-defined problem, the initial and boundary conditions must be provided. The boundary conditions include the heat flux in the mould and under the rollers, forced convection under the nozzles and free convection and radiation in the tertiary cooling zone. The complete numerical model of the temperature field, including boundary conditions in Cartesian and cylindrical coordinates, can be found in.[4]

Equation (1) is discretized by the finite-difference method[3,4] using an explicit formula for the time derivative. The mesh for the finite-difference scheme is non-equidistant and its nodes are adapted to the real rollers and the positions of the nozzles. Equation (1) contains both enthalpy and temperature, so during the simulation the corresponding temperature must be calculated from the enthalpy for each node at each time step. **Figure 2** shows the relationship between the temperature and the enthalpy for three different grades of steel. This numerical model allows us to apply various enthalpy-temperature functions and thermal conductivity-temperature curves, and thus the temperature field can be calculated for various steels, only by defining their chemical composition.

4 OPTIMIZATION ALGORITHM

Our aim is to optimize the continuous casting process by processing its mathematical model. The only parameters we can control are the casting speed and the cooling rates. These parameters are included in the initial and boundary conditions of the model and they can acquire real values from a given continuous bound interval. We need to find their values such that the final temperature field is the best possible. This problem belongs to the area of nonlinear constraint optimization and, therefore, it is usually impossible to obtain the exact solution. We use a method based on nature-inspired metaheuristics called the firefly algorithm.

The main principle is to maintain a group of fireflies where each of them represents one particular solution. These solutions must be comparable with each other in order to be able to decide which one represents a better solution and which one is worse. The algorithm starts with a number of randomly generated solutions (fireflies) and with their evaluations. The evaluation (also called the objective function) describes how much the solution is good and how much it violates the prescribed constraints. During the iteratively repeated algorithm steps, the worse fireflies move towards the better ones and at the end of the computation most of them are concentrated around the best discovered solution. A detailed description of these metaheuristics can be found in.[5]

The firefly, in our implementation, is represented by a vector of fourteen real numbers, the first of which is the casting speed and the next thirteen numbers describe the cooling rates for thirteen cooling circles in the caster. Therefore, the search space of all possible solutions has fourteen independent dimensions and the fireflies moves there according to the aforementioned scheme. The evaluation function is defined as a weighted sum of optimized quantity (casting speed) and values representing the violations of the prescribed metallurgical criteria.

Each evaluation involves one simulation run of the model with parameters related to the actual firefly. This is quite time-consuming because the numerical simulations usually take a long time.

The firefly algorithm is not the only possible method for solving problems like this. It was chosen from a range of other heuristics because of its uncomplicated implementation and its appropriate performance in a real-valued optimization.

5 RESULTS AND DISCUSSION

We implemented the described heuristic algorithm in Python and the numerical model of the temperature field in MATLAB. The communication between them is provided through COM technology. The algorithm was tested on the geometry of a real caster with the steel number S355J0H. The objective function contains the weighted sum of the casting speed, the conditions for the length of the liquid material between 15 and 20 meters, the temperature in the bent part above 1000 °C, the decreasing trend of the temperature courses and the temperature in the exit part between 700 °C and 800 °C. The criteria of the metallurgical length and the exit temperature have to be fulfilled, and thus they have the highest weight. The rest of the conditions have similar weights as each other.

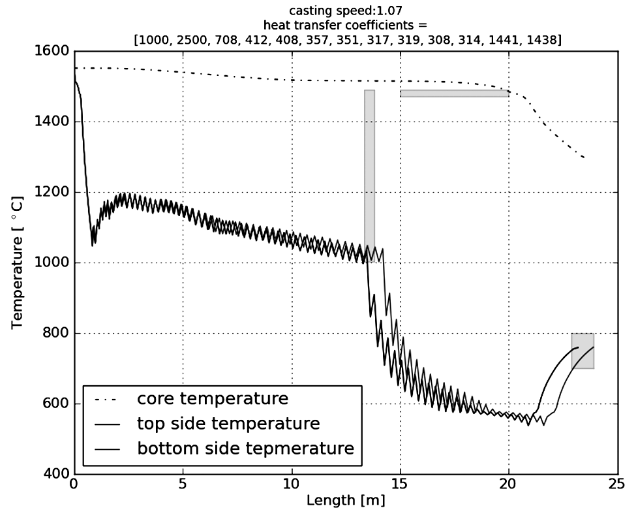

Figure 3: Surface and core temperature
Slika 3: Temperatura površine in jedra

After 10 iterations of 6 randomly chosen fireflies we obtained the result shown in **Figure 3**. It represents temperatures in the middle of the slab, and on its surfaces. The small oscillations are caused by alternating rollers and nozzles and they do not influence the quality of the material significantly.

The optimal speed was found to be 1.07 m/min and the metallurgical length is 19.9 m. If the metallurgical length was not on its maximum it would mean that there is a possibility for increasing the casting speed. But because our metallurgical length is almost 20 m, we have a good indication that we found at least a local extreme. The surface temperatures are above 1000 °C in the whole bent part (up to 13 m) and it keeps the material deformable before the straightening. The temperature in the last part increases, because there are no nozzles and the heat from the kernel is transported on the surface.

The obtained optimal solution fulfils all the prescribed conditions and the steel cast produced with this setting is of high quality and very economical.

6 CONCLUSION

This paper deals with suitable tools for optimization of the slab casting process. We have created an algorithm for the fast and effective casting of high-quality steel. The algorithm controls the cooling rates in the developed numerical model and optimizes it by using the so-called firefly algorithm. The obtained solution complies with all the specified criteria and therefore it can produce cheap final material. The whole method is very flexible and can be modified for an arbitrary grade of steel or quality conditions.

Further research will focus on making the algorithm more precise. This includes the 3D numerical model and the specification of all the conditions that influence the final quality of the cast steel.

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