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A FUZZY-BASED OPTIMAL CONTROL ALGORITHM FOR A CONTINUOUS CASTING PROCESS

ALGORITEM, KI TEMELJI NA MEHKI LOGIKI, ZA OPTIMALNI NADZOR KONTINUIRNEGA PROCESA ULIVANJA

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Nowadays, continuous casting is used for processing almost one hundred percent of liquid steel into an intermediate shape. Steel with a poor structure and many defects is not acceptable to final customers, and therefore the producers must put strong emphases on its quality. Many serious steel defects can be eliminated by a preceding computer simulation, optimization and a proper control of the casting process. This paper describes an algorithm that optimizes the control parameters to ensure both a high production rate and a high quality of the products. These controlled parameters are the casting speed and all the cooling rates in the secondary cooling zone. The main principle of the algorithm is to get the surface and core temperatures to the prescribed values corresponding to the required ductility of steel. The whole optimization procedure consists of two separate parts, i.e., the numerical simulation of the process and the decision-making part based on fuzzy logic for modifying the control parameters. By incorporating the fuzzy logic into the optimization process, the algorithm has a very robust behaviour and an easy adaptation for different grades of steel. This algorithm runs in an off-line version and can be used as a preparation tool for a real casting process where the proper setting of the casting parameters is crucial for achieving high-quality products at an economical price.

Keywords: fuzzy optimization, heuristic optimization, temperature field, continuous casting

Postopek kontinuirnega ulivanja za pridobivanje vmesne oblike se danes uporablja pri obdelavi skoraj stoodstotnega deleža tekočega jekla. Jeklo s slabo strukturo in številnimi napakami ni sprejemljivo za končne kupce, zato morajo proizvajalci veliko pozornosti posvetiti kakovosti jekla. S predhodnimi računalniškimi simulacijami, z optimizacijo in ustreznim nadzorom procesa ulivanja se lahko odpravijo mnoge resne napake jekla. V tem prispevku je opisan algoritem za optimizacijo parametrov nadzora, ki zagotavlja visoko stopnjo proizvodnje ter visoko kakovost izdelkov. Med omenjene parametre nadzora spadata hitrost ulivanja in hitrost ohlajevanja v sekundarni coni ohlajanja. Glavno načelo algoritma je, da površina in temperatura sredice dosežeta določene vrednosti, ki ustrezajo zahtevani razteznosti jekla. Celoten postopek optimizacije obsega dva med seboj ločena dela – numerično simulacijo postopka in pa del, namenjen odločanju, ki temelji na mehki logiki za spreminjanje parametrov nadzora. Z integracijo mehke logike v postopek optimizacije algoritem doseže zelo robustno vedenje in enostavno prilagoditev različnim vrstam jekla. Ta algoritem deluje v različici »off-line« in se lahko uporablja kot pripravljalno orodje za dejanski proces ulivanja, kjer je ustrezna nastavitev parametrov ulivanja ključnega pomena za proizvodnjo visokokakovostnih izdelkov po ekonomični ceni.

Ključne besede: mehka optimizacija, hevristična optimizacija, temperaturno polje, kontinuirno ulivanje

1 INTRODUCTION

Nowadays, continuous casting represents the main method worldwide for forming molten steel into semi-finished products, such as slabs, blooms, and billets. The quality of final products plays one of the most significant roles for customers, and thus to satisfy their demands and maintain the highest possible productivity is a key goal for each steelmaker.

Quality control is a prerequisite for continuous casting and cannot be achieved without a proper knowledge of the main physical influences of the casting process, i.e., the solidification, the micro and macro segregation, the crack formation, etc. During the processing of the steel in the continuous caster, there can arise many problems with its final quality. The solid shell is permanently subjected to thermal and mechanical stresses and this can result in cracks or the breakout of liquid steel through the solid shell. The sources of the mechanical stresses are the friction in the mould, ferrostatic forces, a poor adjustment of the casting speed, roll gaps, bending and straightening of strand, etc. The cracks caused by bending and straightening are influenced by the ductility of steel, and it is well documented that the ductility of steel is reduced over specific temperature ranges depending on the chemical composition[1].

Conducting industrial trials is very expensive, time-consuming and in some cases even impossible, which makes a computer simulation the only sustainable option. There exist various ways of computer or mathematical optimization and each of them has its advantages and drawbacks. Therefore, to ensure the correctness of the algorithm, it is necessary to validate the simulation output using real, measured data.

Previous researches concerned with the optimal control of a continuous casting process were generally based on simplified 1D or 2D temperature-field models[1] and were optimized by mathematical programming or heuristic methods, e.g., genetic algorithms[2], the firefly algorithm[3] or by neural networks. Many of these models are based on simplified assumptions, and therefore they describe the casting process very roughly and not satisfactory. We developed our original numerical model for the temperature field of the real caster and its results were validated by temperature measurements acquired by pyrometers. This more precise model simulates the process controlled by several numerical parameters and the goal is to find their values such that the resultant temperature field is optimal. This algorithm is inspired by our previous research[3] and it is enhanced by a fuzzy logic inference mechanism, which makes its behaviour more robust and its setting easier to adjust.

2 PROBLEM DESCRIPTION AND AN OUTLINE OF THE ALGORITHM

The natural inclination of all steelmakers is to cast as fast as possible but with a preservation of the required material quality. Thus, the problem of optimal casting control can be formulated as follows.

The properties of the final material are highly dependent on its temperature courses emerging during the casting process. Therefore, we need to adjust the parameters of a caster in such a way that the final temperature field is optimal. We can control the process by the regulation of the casting speed and by all the cooling rates in the secondary cooling zone.

Before the optimization starts, it is necessary to define the temperature field, which leads to the optimal material and mechanical properties. These optimal temperature courses are defined by experts (casting operators, material scientists, etc.) and they differ with the chemical composition of the steel.

To deal with the high variability of the described problem, the heat and mass phenomenon must also be taken into account, and therefore the employed numerical model has to cover all the phase and structural changes. The search for the optimal cooling rates and the highest possible casting speed is left to the following fuzzy-logic heuristic algorithm.

To describe the optimal temperature field, the experts define a set of points along the caster and prescribe their optimal temperature ranges. Then the algorithm randomly generates the values for all the input parameters and simulates the final temperature field. After comparing the computed temperatures with the prescribed ones, the algorithm decides which nozzles need to be adjusted and how to change the casting speed. Particular decisions for changing the values are taken by the fuzzy inference logic. These steps are iteratively repeated until the required temperatures are successfully reached.

3 MATHEMATICAL MODEL OF THE TEMPERATURE FIELD

The developed numerical model of the 2D temperature field computes the formation of the solidification and the temperature distribution of the cast strand. This temperature field is modelled by the Fourier-Kirchhoff equation[1–3], where the velocity component v_y(m/s) is considered only in the direction of casting:

$$\frac{\partial H}{\partial \tau} = k_{\text{eff}}\,(T)\Delta(T) + v_y\,\frac{\partial H}{\partial y} \tag{1}$$

Equation (1) describes a transient heat transfer, where k_{eff}/(W/m K) is the effective thermal conductivity, T/K is the temperature, H/(J/m^3) is the volume enthalpy, τ/s is the time and x and y are spatial coordinates. The phase and structural changes are included in the model by the latent-heat accumulation method, where the enthalpy is used as the primary variable and the temperature is calculated from a defined enthalpy-temperature relationship[3]:

$$H = \int_0^T \left(\rho(\xi)c(\xi) - \rho(\xi)\Delta H \frac{\partial f_{\text{s}}}{\partial T} \right) \mathrm{d}\xi \tag{2}$$

where ΔH/(J/kg) is the latent heat, ρ/(kg/m^3) is the density, c/(J/kg K) is the specific heat capacity and f_{s} is the solid fraction.

In order to have a well-posed problem, the initial and boundary conditions must be stated. The boundary conditions include the heat fluxes in the mould and under the rollers, the forced convection under the nozzles and the free convection and radiation in the tertiary cooling zone. 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 nozzle positions. Our 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 just by redefining the chemical composition.

Thermo-physical parameters such as the thermal conductivity, the density, the specific heat capacity and the enthalpy and their temperature dependence are computed from a specific chemical composition of steel by using the solidification analysis package IDS.

The numerical model is designed and verified for the radial slab caster operating in EVRAZ VÍTKOVICE STEEL, a. s. The caster contains 12 coolant circuits and the cross-section of the investigated slab is 1550 mm × 250 mm.

4 DESCRIPTION OF THE ALGORITHM

The algorithm searches for the optimal values of the control parameters (cooling rates and the casting speed). The inputs to the algorithm are the required temperature ranges in the points along the caster and the maximum metallurgical length. For each cooling circuit, the maximum cooling rate is defined. The initial value of each control parameter is randomly chosen from the permitted range and the model is consequently evaluated by the numerical simulation. From the computed result, the algorithm extracts temperatures in the controlled points and by a comparison with the prescribed values determines their deviations (errors). Also, the metallurgical length (the length from the meniscus to the point where the steel is fully solidified) is computed. Using all this information the algorithm infers the modifications for all the controlled input parameters.

The temperature courses at the controlled points are dominantly influenced by the two preceding coolant circuits. The closer circuit has a greater influence. Therefore, each coolant circuit defines a numerical value for each controlled point that describes how much it impacts on the temperature in the controlled point. These values are expertly estimated (in the range from 0 to 10) and they are strongly related to the distance from the controlled points.

In the presented model there are two fuzzy inference mechanisms – one for the modification of the cooling rates and one for the control of the casting speed.

The inference rules for the cooling rates have the following form: "IF error IS *adj1* AND impact IS *adj2* THEN modification IS *adj3*". For each controlled point the *adj1* describes the temperature error, the *adj2* is the cooling impact of the given circuit and the *adj3* is the modification inferred for the cooling rate. **Table 1** shows all the rules in the matrix form.

Table 1: The dependences of adj3 on adj1 and adj2. The abbreviations stand for Very Small, Small, Medium, Big and their fuzzy sets are equidistantly distributed along the corresponding universes.

Tabela 1: Odvisnost označevalca 3 od označevalca 1 in označevalca 2. Okrajšave pomenijo VS – zelo majhen, S – majhen, M – srednji, B – velik, njihove mehke nastavitve pa so v enakih razdaljah razporejene po ustreznih splošnih parametrih.

adj2 / adj1	VS	S	M	B
S	VS	VS	S	S
M	VS	VS	S	M
B	VS	S	M	B

Sometimes, one circuit can get several different modifications and if it happens the algorithm takes the one with the highest absolute value. The defuzzification method is the standard centre-of-gravity function. If the maximum absolute value of all the temperature errors does not exceed a particular limit, the algorithm consequently computes the modification for the casting speed. The reason for introducing the limit is that if the maximum error is too big (i.e., the solution is far from the optimum), we have no information about whether the speed is high or not and at first it is better to stabilize the process and then to infer the speed modification.

The rules for the modification of the casting speed (**Table 2**) are in the form: "IF maximum_error IS *adj4* AND metalurgical_length IS t*adj5* THEN modification IS *adj6*". The *adj4* describes the maximum error over all the controlled points, the *adj5* is the metallurgical length and the *adj6* is the inferred modification of the casting speed.

For a detailed explanation of the fuzzy logic and the fuzzy inference, see[5].

The values of the impacts for each cooling circuit to the controlled point are chosen to be 8 for the closest preceding circuit and 2 for the circuit placed before (except the last controlled point, where the distance to the second closest circuit is much longer, and therefore the values are 9 and 1).

Table 2: The dependences of adj6 on adj4 and adj5. The abbreviations stand for Very Small, Small, OK, Big, Very Big and More, Little More, Little Less, Less, Nothing and their fuzzy sets are equidistantly distributed along the corresponding universes.

Tabela 2: Odvisnost označevalca 6 od označevalca 4 in označevalca 5. Okrajšave pomenijo VS – zelo majhen, S – majhen, OK, B – velik, VB – zelo velik in MO – več, LM – malo več, LL – malo manj, L – manj, N – nič, njihove mehke nastavitve pa so v enakih razdaljah razporejene po ustreznih splošnih parametrih.

adj4 / adj5	VS	S	OK	B	VB
S	MO	LM	LM	LL	L
M	LM	N	N	N	LL

5 RESULTS OF EXPERIMENT

The examined grades of steel are the low-carbon steel S355J0H and the high-carbon steel X210CrW12. The expertly defined temperature ranges in the controlled points are depicted in **Figure 1** and **Figure 2** (the grey rectangles). The crucial reason for defining these temperature ranges in this way is that approximately the first half of caster is curved and therefore to decrease the mechanical stresses it is better to keep the temperature

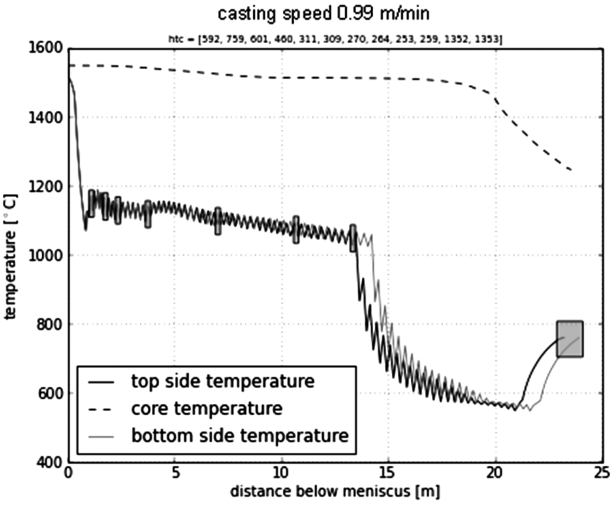

Figure 1: Final temperature distributions (S355J0H)
Slika 1: Končne razporeditve temperature (S355J0H)

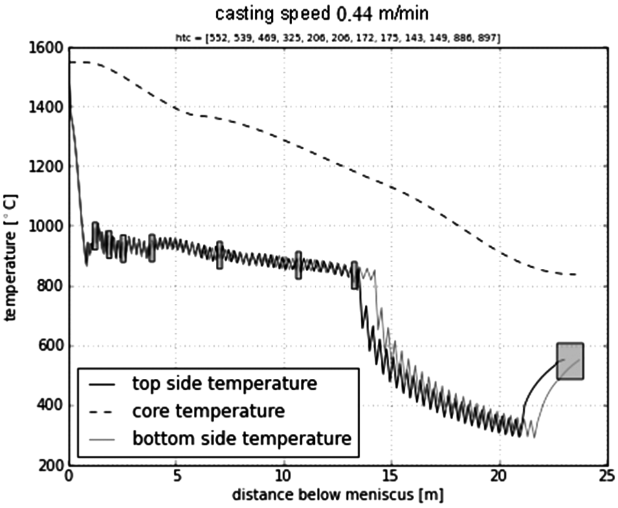

Figure 2: Final Temperature distributions (X210CrW12)
Slika 2: Končne razporeditve temperature (X210CrW12)

above a certain level (for S355J0H, 1000 °C, and for X210CrW12, 800 °C). The value of the maximum metallurgical length is 20 m (from the practice) and the casting temperature is 1550 °C. Reaching the temperature courses on surface ensures that the mechanical and material qualities of the final material will satisfy the demands. The optimal values computed by this algorithm (casting speed and heat-transfer coefficients) are shown in **Figure 1** and **Figure 2**.

Usually, the most important indicator characterizing the efficiency of iterative optimization algorithms is the number of evaluations of the model. The computation of the numerical model is very time-consuming, and therefore each repetition can significantly prolong the computations. Our algorithm is able to find the optimal input parameters in 50 evaluations, on average. The tests ran several times for different grades of steel and the number of evaluations never exceeded 65. The computation time takes a few hours.

6 CONCLUSION

The problem of the optimization of a continuous casting process can be efficiently solved by the described algorithm. The algorithm based on heuristics and incorporating the fuzzy logic behaves in a very robust way and it is easily adaptable to any grade of steel and caster geometry. The number of evaluations of the included numerical model is low, and thereby the algorithm proves its high efficiency. Further research will be focused on extending the numerical model to 3D and a generalization of the used optimization constraints.

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