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OPTIMIZATION OF THE SECONDARY COOLING IN A CONTINUOUS CASTING PROCESS WITH DIFFERENT SLAB CROSS-SECTIONS

OPTIMIZACIJA SEKUNDARNEGA HLAJENJA PRI KONTINUIRNEM ULIVANJU SLABOV Z RAZLIČNIMI PREREZI

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Although the continuous casting of steel began almost 60 years ago, its production still suffers from many serious defects in the final structure. Cracks in the solidifying slab are mainly caused by variable thermal conditions and mechanical stresses. It is well known that the secondary cooling zone has an important effect on the internal and surface quality. Thus, the optimal control of the cooling intensity in secondary cooling is inevitable in order to obtain high-quality products. Nowadays, the control of the slab temperature via numerical temperature-field models is a common practice for controlling the quality of the slabs. This leads to cooling regulation according to the actual casting speed, casting temperature, cross-section of casting slab, chemical composition of steel, etc. Unfortunately, the actual practice in many steelworks is that the cooling regulation is determined as a simple linear function of the casting speed. In order to deal with this problem, the fuzzy-optimization algorithm and numerical model of the temperature field were created. Their combination can provide instructions for how to control the secondary cooling and obtain high-quality of steel. This paper mainly describes the differences between the optimal cooling of different slab cross-sections (width between 800 mm and 1600 mm, thickness between 180 mm and 250 mm). The results show that the proper setting of secondary cooling cannot be done without a consideration of all the main casting factors.

Keywords: secondary cooling, fuzzy optimization, temperature field, continuous casting

Čeprav je kontinuirano ulivanje jekla poznano že skoraj 60 let, se v proizvodnji še vedno pojavljajo številne resne napake slabov. Razpoke pri strjevanju slaba so v glavnem posledica spremenljivih toplotnih razmer in mehanskih napetosti. Znano je, da ima sekundarna hladilna cona pomemben učinek na kakovost notranjosti in površine. Zato je za visoko kakovost proizvoda neizogibna optimalna kontrola intenzivnosti sekundarnega hlajenja. Danes se zagotavlja kontrola slabov z uporabo numeričnih modelov temperaturnega polja. To vodi do regulacije ohlajanja, skladno z dejansko hitrostjo ulivanja, temperaturo ulivanja, prereza ulitega slaba, kemijske sestave jekla itd. Da bi obvladali te težave, sta bila postavljena algoritem mehke optimizacije in numerični model temperaturnega polja. Njuna kombinacija lahko da napotke, kako kontrolirati sekundarno hlajenje in zagotoviti veliko kvaliteto jekla. Ta članek opisuje razlike med optimalnim ohlajanjem različnih prerezov slabov (širine med 800 mm in 1600 mm in debeline med 180 mm in 250 mm). Rezultati kažejo, da pravilna nastavitev sekundarnega hlajenja ni mogoča brez upoštevanja glavnih dejavnikov pri ulivanju.

Ključne besede: sekundarno hlajenje, mehka optimizacija, temperaturno polje, kontinuirano ulivanje

1 INTRODUCTION

Nowadays, more than 95 % of the world's steel production is being produced by continuous casting (CC).[1,2] Using CC molten steel is formed into semi-finished products such as slabs, blooms and billets. The CC installation is divided into three parts. The water-cooled mold (primary cooling zone), secondary cooling where the steel is transported by rollers and cooled down by groups of nozzles, and the tertiary cooling zone where the surface is cooled down by free convection and radiation only. The importance of the intensity of cooling in the secondary cooling is well known and has been discussed in many papers.[1,3,4] These papers give the casting recommendations and possible mathematical tools which can be applied in the real system.

Unfortunately, the practice in many steel works does not reflect the actual state of the art in this field and the regulation of the secondary cooling is far from optimum. There can be many reasons for this. Some steel workers are not progressive enough; many papers are rather theoretical and the validation is not sufficient; mathematical models and optimization algorithms are often less general than is necessary; etc.

This paper deals with optimal cooling curves in the secondary cooling zone for different slab cross-sections (width 800–1600 mm, thickness 180–250 mm). These cooling curves were found by using a combination of numerical modeling and the optimization technique. The next section describes the modeling concept, but for a detailed description we recommend our previous work.[5,6]

2 DESCRIPTIONS OF THE MATHEMATICAL ALGORITHMS

The mathematical part of the research is created by two models. The first model is a numerical model of the temperature field based on the governing equation of transient heat conduction, also called the Fourier-Kirchhoff equation:[1,5]

$$\frac{\partial H}{\partial \tau}+v\frac{\partial H}{\partial z}=\nabla(k_{\mathrm{eff}}(T)\nabla T) \tag{1}$$

where k_{eff} (W/mK) is the effective thermal conductivity, T (K) is the temperature, H (J/m^3) is the volume enthalpy, τ (s) is time and v (m/s) is the casting speed and z (m) is the direction of casting. This model represents a unique combination of numerical modeling and a large number of experimental measurements.[7] The model is able to predict the temperature distribution in the whole slab, the solid shell thickness and the position of the metallurgical length (the distance below the meniscus). Its results are validated by measurements in the real casting process. In order to speed up the computational time, the model could run in a parallel GPU (Graphic Processing Unit) architecture.[8]

The second model is the optimization/regulation algorithm based on fuzzy logic. The model is created with the aim to optimize the parameters of the casting for a given particular grade of steel, cross-sections of the slab, casting temperature, casting speed, etc. **Figure 1** shows a block scheme of the connection between the regulator and the numerical model. The fuzzy regulator is subordinated to the numerical model and in every time iteration the regulator progressively tunes the cooling parameters as the closed-loop system.

The optimization strategy is to keep the surface and core temperatures in the specific ranges corresponding with the hot ductility of the steel.[9] The reason for this is to avoid surface and core defects.

The presented concept creates a very general approach to optimally control any CC process (geometry of the slab, steel grades, caster geometry, casting limitation such as allowed casting speed, water flows in secondary cooling, etc.). Moreover, the algorithm can be used for both off-line and on-line regulation. The example of an optimal result is shown in **Figure 2** for the steel grade S355J0H. **Figure 2** shows the temperature distribution at the slab surface in different positions and the temperature distribution in the slab core. The black boxes are the recommended temperature intervals at the slab surface to ensure the good surface quality of the steel.

The most important indicator of iterative optimization algorithms is usually the number of evaluations of

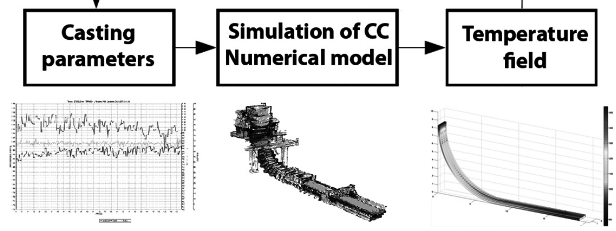

Figure 1: Block scheme of the regulation approach
Slika 1: Shematski prikaz načina regulacije

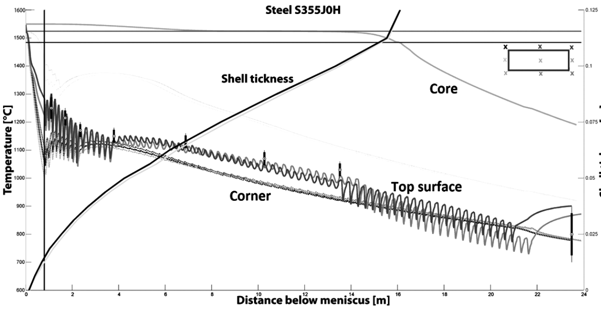

Figure 2: Temperatures distribution after fuzzy regulation
Slika 2: Razporeditev temperature po mehki regulaciji

the problem. The evaluation of the numerical model is very time consuming and therefore each repetition can significantly prolong the computation. Our algorithm was able to find the optimal parameters in less than 30 evaluations, on average. The tests were run several times for the different grades of steels and with completely random initial states and the number of evaluations never exceeded 50. The results shown in **Figure 2** were obtained after 27 evaluations.

3 RELATIONSHIP BETWEEN CASTING SPEED AND COOLING INTENSITY

The steelmakers operating with CC of slabs are forced by their customers to cast different slab cross-sections. The width of the slab is generally from 800 mm to 1600 mm and thickness of slab from 180 mm to 250 mm, depending on the caster installation. Each slab cross-section has typical defects. In order to avoid these defects the caster should be set-up with a consideration of the slab cross-section.

The casting process is influenced by many parameters, but only a few of them can be controlled in reasonable ranges. For instance, controlling the casting temperature is not really possible and the safety protocols restrict the water flows through the mold. The typical control parameters are the casting speed and the cooling intensity in the secondary cooling zone.

The goal of the optimization is to set the casting speed as high as possible and still keep the good quality of the cast steel. Controlling the surface quality can be achieved by the presented temperature intervals in certain points (the black boxes in **Figure 2**, the so-called control points), while the inner quality is influenced by the position of the metallurgical length. Thus, there are two optimization constraints: the limitation of the metallurgical length and the artificial value, the so-called maximum error (the sum of temperature residuums in the controlled points).

The search for the optimal relationship between the casting speed and the cooling intensity is simply based on a gradual increase of the casting speed (from 0.7 m/min to 1.3 m/min). The algorithm for every value of the casting speed is able to find a corresponding cooling

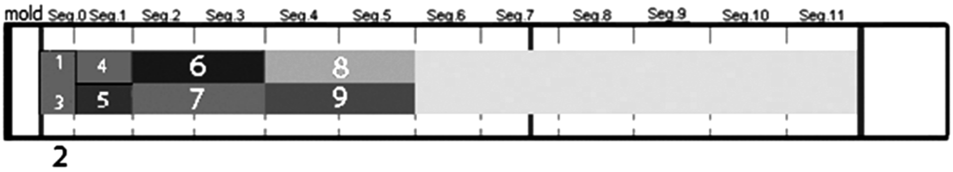

Figure 3: Position of cooling circuits
Slika 3: Položaj hladilnih tokokrogov

intensity. From the optimization results the data where the metallurgical length exceeded the given limit (from 14 m to 24 m) and where the maximum error exceeded 100 °C were discarded.

4 RESULTS AND DISCUSSION

The results were calculated for a casting machine SMS Demag. The caster specifications are in **Table 1**. The number of independent cooling circuits is nine, placed according to **Figure 3**. The examined grade of steel is typical low-carbon steel from Steel Group 4 No. 4038 specified by the chemical composition in **Table 2**.

Table 1: Slab caster machine specification
Tabela 1: Lastnosti naprave za ulivanje slabov

Ladle capacity	180 t
Tundish capacity	40 t
Mold level control	Berthold mould level measuring system
Torch cutting machine type	
Slab Marking Machine type	
Caster Machine has 9 cooling loops and electrical mold oscillation system	
Width	650–1880 mm
Length short slab	4.5–4.75 m
Length long slab	9.1–9.9 m

Table 2: Chemical composition of examined steel (*w*/%)
Tabela 2: Kemijska sestava preiskovanega jekla (*w*/%)

C	Si	Mn	Cr
0.190	0.250	1.350	0.035
Ni	Mo	Cu	Al
0.045	0.035	0.045	0.040
Nb	Ti	V	
0.005	0.005	0.005	

The optimal cooling curves were calculated for the three frequently cast slab cross-sections, 1600 mm × 250 mm, 1200 mm × 200 mm, and 800 mm × 180 mm. The results are shown (**Figures 4** to **7**) for the cooling circuits on the top surface where the risk of the occurrence of cracks is higher than on the bottom surface.

The metallurgical length and temperature intervals on the surfaces restrict the allowed casting speed range for all the simulated slab cross-sections. For instance, the slab cross-section 1600 mm × 250 mm has a recommended casting speed interval of between 0.7 m/min and 1.0 m/min. This result was expected, but the casting limits are slightly different than the casting limits presented by the casting equipment. The most flexible casting range is for the 1200 mm × 200 mm slab, while the most critical interval is for the 800 mm × 180 mm slab, and it probably needs special treatment. There are more reasons for this, but we should realize that this caster was mainly designed to cast larger cross-sections.

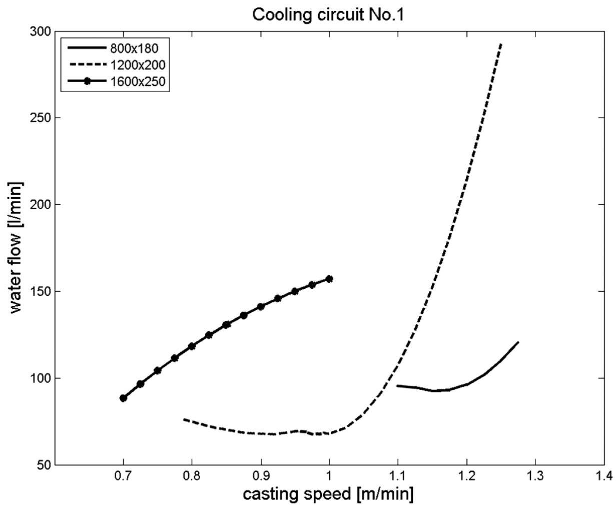

Figure 4: Optimal cooling curves for cooling circuit No. 1
Slika 4: Optimalne krivulje hlajenja za hladilni krog št. 1

The second problem is the shape of the cooling curves. The initial hypothesis that the linear relationship between the casting speed and cooling intensity is not suited is the clearly seen from **Figures 4** to **7**. The cooling results were fitted by both linear and quadratic regression. The results with the higher value of the

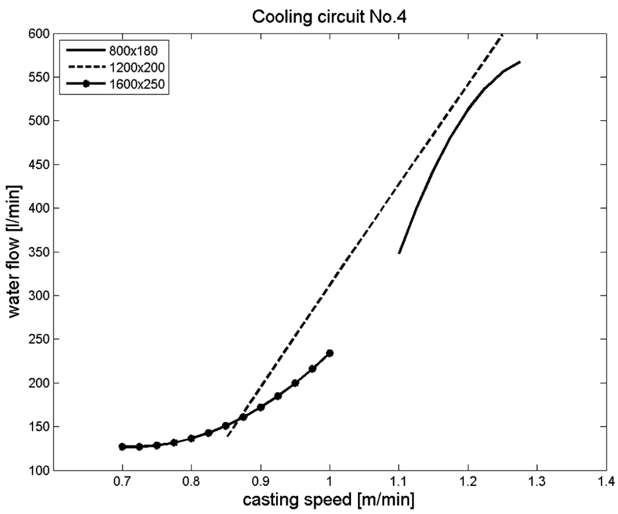

Figure 5: Optimal cooling curves for cooling circuit No. 4
Slika 5: Optimalne krivulje hlajenja za hladilni krog št. 4

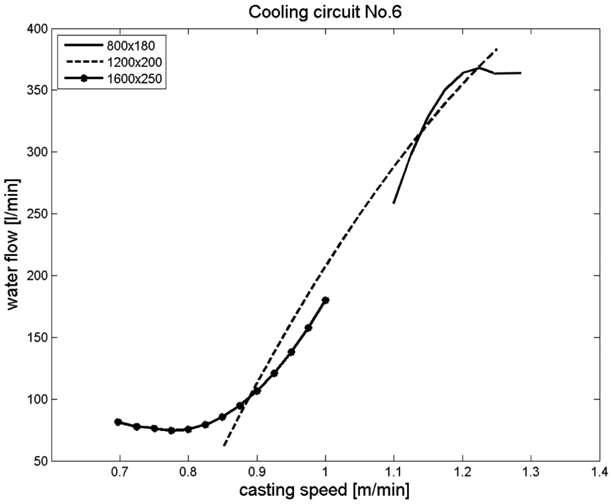

Figure 6: Optimal cooling curves for cooling circuit No. 6
Slika 6: Optimalne krivulje hlajenja za hladilni krog št. 6

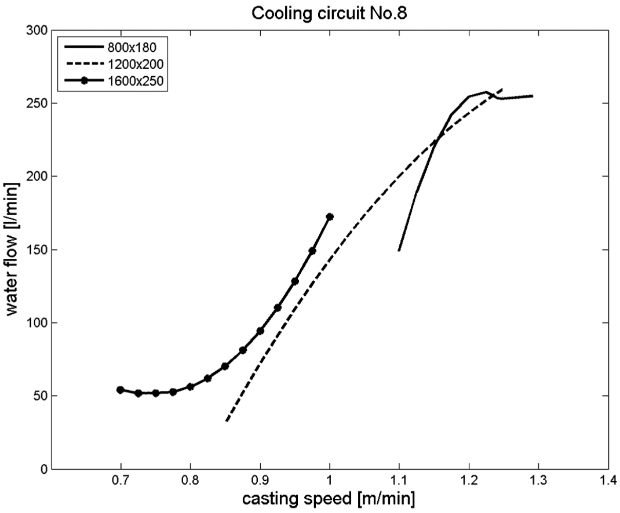

Figure 7: Optimal cooling curves for cooling circuit No. 8
Slika 7: Optimalne krivulje hlajenja za hladilni krog št. 8

coefficient of determination were chosen. Only for the cooling circuit No. 5 and for the slab cross-section 1200 mm × 200 mm the linear regression has better results than the quadratic. But the rest of them were clearly non-linear.

5 CONCLUSION

The problem of optimally cast steel for different slab cross-sections can be efficiently solved using the described algorithm. The algorithm based on numerical modeling with fuzzy logic is very robust and is easily adaptable to any grade of steel, caster and slab geometry, etc. The results show that the casting of steel slabs should be made according to more casting indicators than just the casting speed. The cooling behavior is different for the different slab cross-sections and the steelmaker should take into account this fact. Otherwise the steel product will still be cast with the surface and the core defects.

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