QUALITY IMPROVEMENT OF CONTINUOUSLY CAST SPECIAL STEEL BY USING NUMERICAL-OPTIMIZATION MODEL

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Abstract

Optimal regulation algorithms and complex numerical simulations are utilized in contemporary production processes. High quality of products, minimum of scrap, and reduction of carbon footprint are current trends in industry processes including the continuous casting process of steel. The paper shows a utilization of the 3D transient solidification model and an original fuzzy regulator for the improvement of the surface slab quality in the continuous casting of a high-strength low-carbon steel. An optimal casting scenario was proposed based on the real casting measurement and statistical evaluation. The relationship between the temperature history of the slab surface and the number of surface defects was statistically evaluated. Based on statistical data, the fuzzy regulator and the solidification model were used to find an optimal cooling strategy as a function of the casting speed and of the casting temperature. Though results are demonstrated for a specific slab caster and for a specific grade of steel, the presented concept is general from its nature and it can be used for any caster or any grade of steel.

Keywords: Continuous casting, fuzzy optimization, secondary cooling, steel quality

1. INTRODUCTION

The quality of steel in the continuous casting (CC) process is discussed in many papers [1, 2]. Generally for steelmakers it is vital to minimize the number of rejected slabs which need to be scraped, to improve the overall quality of steel sheets, but to preserve high productivity of casting. These challenges can be handled by using statistic methods, advanced numerical modelling and optimization-regulation techniques. There are many papers which combine numerical modelling and optimization-regulation approaches such as [3, 4, 5]. Unfortunately, the numerical models in these works were often very simplified without validation with the real casting process. This paper describes the statistical evaluation of real casting data and the usage of the original 3-D heat transfer and solidification model, the so-called Brno Dynamic Solidification Model® (BrDSM, see www.continuouscasting.info) with advanced optimal control tools for the high steel quality and the casting productivity improvement based on the fuzzy-logic regulation. The demonstration of the presented approach is shown on the EVRAZ VITKOVICE STEEL radial slab caster with twelve cooling loops in the secondary cooling zone and with a special grade of steel S355 for ocean offshore structural projects.

2. SOLIDIFICATION MODEL AND FUZZY REGULATION

The solidification model BrDSM numerically solves 3-D transient heat and mass transfer phenomena with non-isothermal phase changes from liquid to solid steel based on the enthalpy method [6]. The numerical discretization is based on a non-equidistant fine mesh and the simple explicit scheme which allows for massively-parallel Graphic Processing Unit (GPU) calculations. This approach is very suitable for the combination with the optimal (predictive) control algorithm because it allows calculating the BrDSM with a very fine mesh several-times faster than the real time. The boundary conditions at the mould were determined by measurements of inlet and outlet cooling water temperatures and the heat flux layout can be computed from the average value using additional information of a matrix of thermocouples in the mould wall. The boundary conditions at the secondary cooling area were measured in Heat Transfer and Fluid Flow Laboratory for all nozzles used at the caster with the use of the so-called hot plate method according to [7]. The visual part of the user interface can be seen in **Figure 1**. The detailed description of the BrDSM including boundary conditions, numerical model discretization, mesh size convergence, secondary cooling distribution, etc. is described in [8].

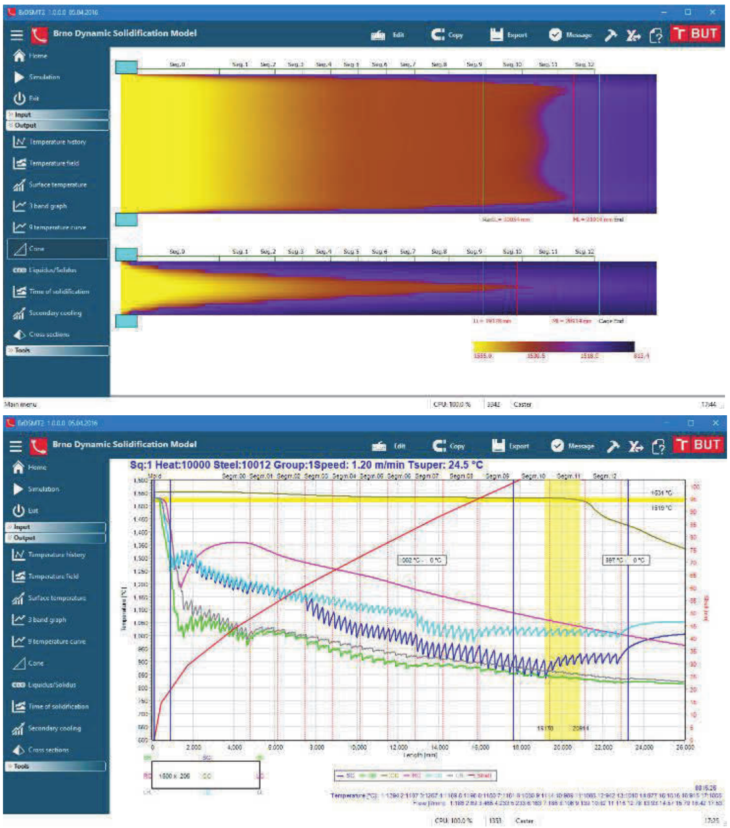

Figure 1 BrDSM interface

The BrDSM can calculate the temperature distribution of the strand for given casting parameters such as the initial temperature distribution, intensity of cooling, speed of casting, etc. The problem is how to set input parameters in an optimal way to get a required (optimal) temperature distribution which ensures a good quality of steel. This is referred to as an inverse problem. For this purpose the original supervision system based on the fuzzy logic was developed. Our supervision system evaluates simple rules such as if the temperature is low then decrease the cooling intensity, or if the temperature is very low then decrease cooling even more, etc. **Figure 2** shows the block scheme of the fuzzy regulator and BrDSM. The fuzzy regulator *compares results from the BrDSM with "optimal"* required temperature field. Based on the difference between actual and optimal temperature field, the fuzzy regulator tunes cooling intensities in a closed-loop until an

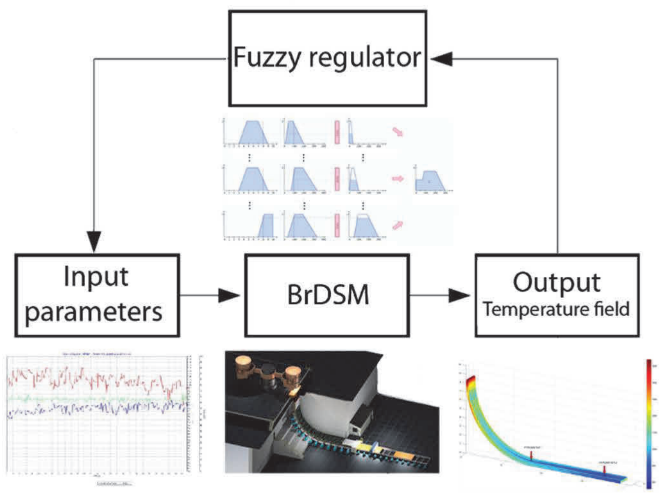

Figure 2 Fuzzy-BrDSM scheme

optimal solution is found. The detailed description of the fuzzy regulator and of the solidification model including linguistic variables, linguistic rules, etc. is described in [8].

The most important parameter for the fuzzy regulator is to define an optimal surface temperature curve. The optimal cooling strategy must keep the surface temperature inside intervals around the optimal surface temperature curve. The word optimal stands here for the state where no or minimum surface defects can originate. These intervals are set by the user and they are distinct for different grades of steel. How the intervals were set in the paper will be discussed in Section 3. The fuzzy regulator was tested for different casting conditions and setting of parameters. The system concept was universally designed in order to optimally control any slab or billet CC process. The main advantage is a small number of evaluations before the optimal solution is reached so the system can be used for transient simulations and for on-line casting process control. The combination of the fuzzy regulator with the GPU solidification model can predict future temperature states and it works like the model predictive control system.

3. STEEL S355, REAL CASTING DATA AND OPTIMAL TEMPERATURE INTERVAL

A frequent occurrence of surface defects on slabs of the cast steel grade S355 was the reason for statistical and numerical investigation. This steel was selected expediently because it is mainly used for shipbuilding projects, marine mechanical systems and deepwater ocean offshore structural projects where the quality of steel plates is essential. The breakdown situation caused by a low quality of steel could have a catastrophic effect on material and human losses. The chemical composition is listed in **Table 1**. Thermophysical properties of steel S355 were calculated by using the IDS solidification package and solidus and liquidus temperatures were compared with dynamic thermal-analysis methods [9].

Table 1 Chemical composition of steel S355

	Ni	Mn	Mo	Si	Nb	Ti	Cu
wt%	max 0.30	1.4-1.55	max 0.08	0.5	max 0.06	max 0.02	max 0.20
	V	Al	P	C	Cr	S	Ca
wt%	max 0.02	0.02-0.06	0.03	0.16-018	max 0.20	0.02	0.0019

Three typical defects were found: transverse facial cracks, star cracks and longitudinal facial cracks. The most common defect was the star crack, see **Figure 3**. These defects primarily appear at the top surface of the strand and possible reasons for these defects are hard cooling and tensile stresses at the straightening area [3]. Therefore, the top surface of the strand and the temperatures at the straightening area were investigated.

Figure 3 Typical star crack defect

The real casting data were statistically evaluated from approximately 2000 heats cast in 2011 and 2012 in EVRAZ VITKOVICE STEEL machinery in the Czech Republic. The evaluation of the statistical hypothesis shows that the surface temperature in the unbending point significantly influences the surface quality of slabs. The heats were divided into two groups, heats where surface defects were found and heats without surface defects. The surface temperature was measured by a pyrometer at the straightening area, see **Figure 4 - 5**.

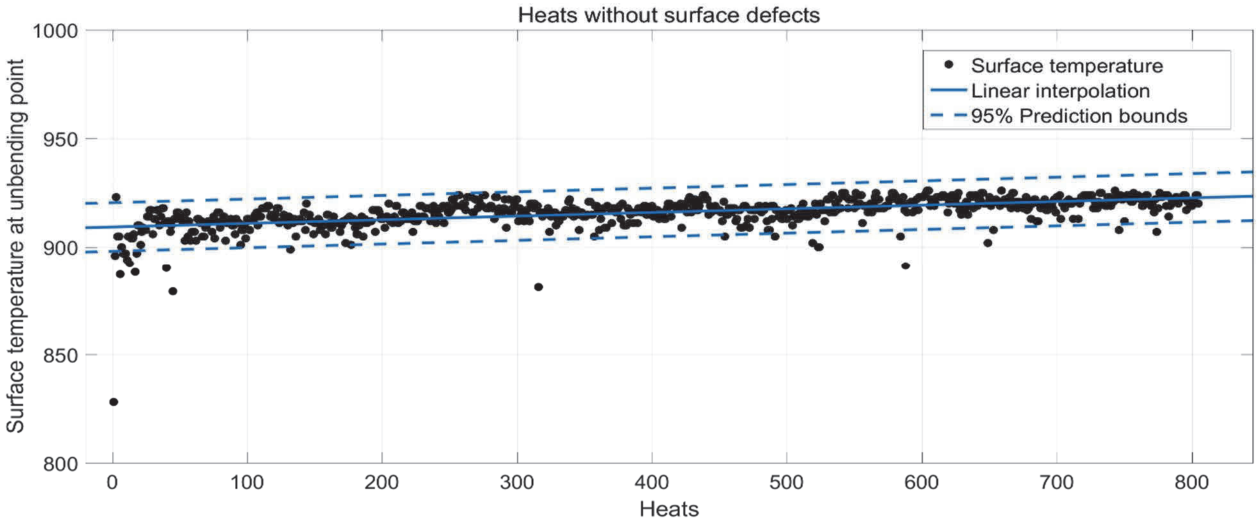

Figure 4 Surface temperatures with 95 % prediction bounds (without defects)

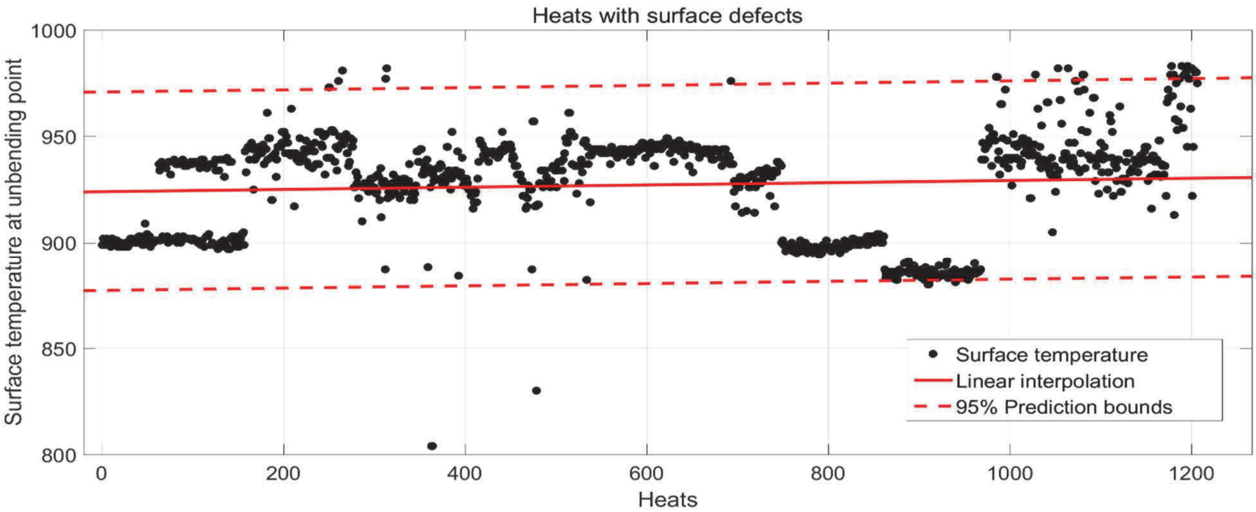

Figure 5 Surface temperatures with 95 % prediction bounds (with defects)

Hypothesis tests show that we cannot reject the hypothesis on the 5 % level of significance stating that the surface temperature at the straightening area influences the presence of surface defects. This leads to the following idea: if we will keep the surface temperature in some range, the occurrence of surface defects would be minimized. The mean surface temperature from heats without defects was 916.03°C with the standard deviation 6.89 °C while the mean surface temperature from heats with defects was 927.14 °C with the standard deviation 23.90 °C. The statistical results were used as the input for Fuzzy-BrDSM.

4. RESULTS AND DISCUSSION

The temperatures from three positions (mold exit area, straightening area and caster exit area) measured by pyrometers were fitted by the exponential function $y = a \cdot x^b + c$, where y is the required temperature, x is the distance from meniscus and a, b and c are the parameters of the exponential function. The surface defects occurred in heats with high temperature fluctuations in the straightening area. From this point of view the upper and lower allowed limit was only 5 °C above and 5 °C below the optimal temperature in the straightening area (see **Figure 6**).

The strand temperature history for the casting speed 0.8 m / min is shown in **Figure 6**. The cross-section size of the slab was 1530 × 250 mm and the numerical mesh was created from over 1.5 million nodes. Because the CC is a dynamic process, the casting speed and temperature of overheating (casting temperature - liquidus temperature) vary in time, it is necessary to keep surface temperatures at constant values in order to receive a high steel quality. Thus, optimization was carried out for different casting speeds and for different temperatures of overheating in order to obtain the optimal relationship between cooling intensities and the casting speed/temperature, see **Table 2**. The casting intensity for four cooling loops is shown in **Figure 7**.

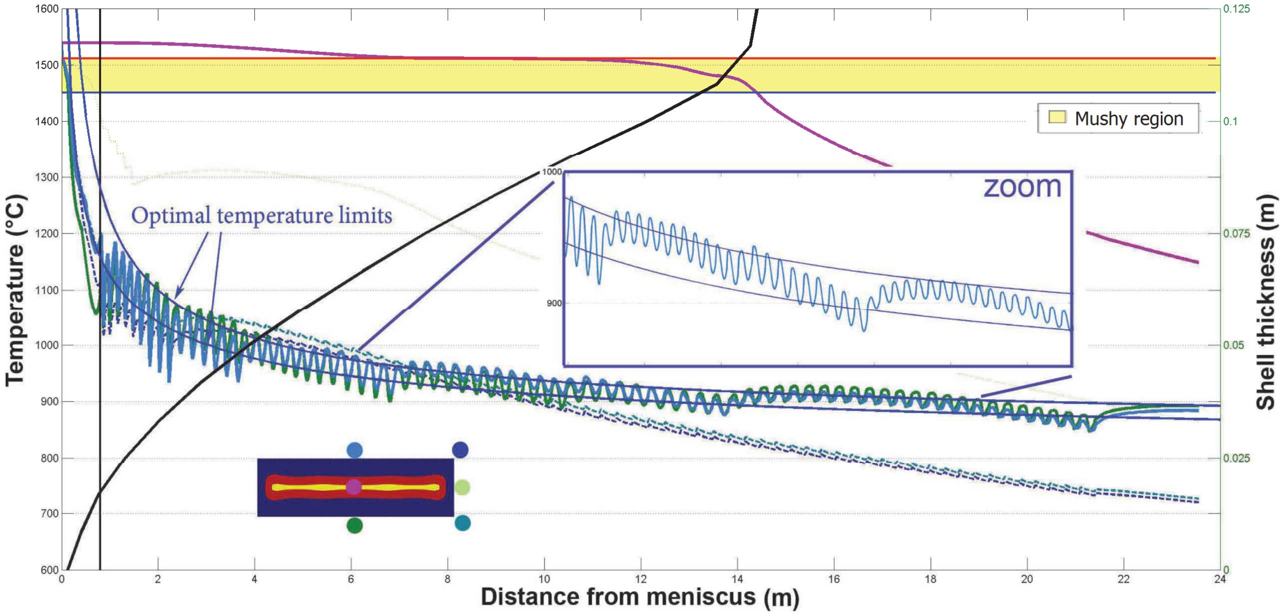

Figure 6 Optimal temperature field

Table 2 Cooling intensity for different casting conditions

Overheating temperature	Casting speed	Loop 1	Loop 2	Loop 3	Loop 4	Loop 5	Loop 6	Loop 7	Loop 8	Loop 9	Loop 10	Loop 11	Loop 12
30.00	0.80	96	124	102	129	69	99	28	62	22	33	31	57
30.00	0.85	97	126	105	128	83	102	35	78	22	41	51	86
30.00	0.90	98	129	105	147	98	99	46	102	29	68	92	128
30.00	0.95	102	139	128	148	100	112	60	98	39	75	124	136
28.00	0.80	97	125	101	124	67	99	28	66	22	30	31	50
28.00	0.85	97	126	102	126	83	102	37	74	26	48	58	76
28.00	0.90	98	130	108	148	97	104	49	87	28	65	86	103
28.00	0.95	103	142	128	148	100	112	58	97	35	79	126	139
26.00	0.80	97	126	101	123	67	99	26	61	22	33	31	48
26.00	0.85	97	126	102	126	81	101	37	75	28	45	57	70
26.00	0.90	98	129	108	148	98	104	44	91	30	65	91	128
26.00	0.95	102	139	128	148	101	111	58	97	38	75	129	134
24.00	0.80	97	126	101	123	68	98	28	61	22	31	31	54
24.00	0.85	97	126	103	126	80	101	35	74	22	42	56	72
24.00	0.90	98	129	107	145	97	104	44	87	27	62	91	109
24.00	0.95	103	139	128	148	100	112	60	98	37	75	128	133

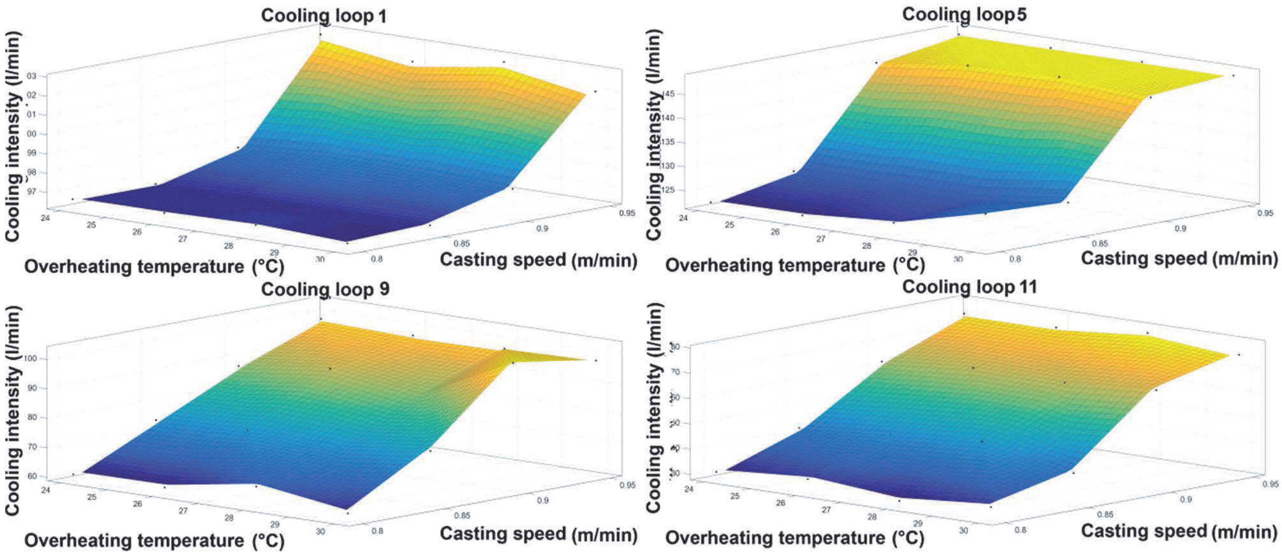

Figure 7 Optimal cooling intensity for four particular cooling loops

The cooling intensity for zones 5 and 9 reaches its maximal allowed values for casting speeds of 0.9 m / min and 0.95 m / min. This means that even a better solution probably exists for a higher cooling capacity at these zones. Moreover, a higher casting speed can also be reached.

5. CONCLUSION

The Fuzzy-BrDSM was tested for many different fuzzy parameters, for different casting temperatures and casting speed constraints, for different caster and slab geometries, and for different steel grades and it proved robust and stable solutions. This paper is focused on the quality improvement of the particular special steel grade S355 where high quality of steel plates is vital. The first part of the work was focused on the statistical evaluation of real historical casting data (over 2000 heats). The influence of the surface temperature in the straightening area on the occurrence of surface defects was statistically evaluated as significant. From statistics the optimal surface temperature curve and its intervals were determined and used as the input for Fuzzy-BrDSM. The optimal cooling intensities in the secondary cooling zone were found for different casting speeds and for different temperatures of overheating. The use of recommended cooling curves in the real casting process can lead to the minimization of surface defects in casting of the special steel grade S355. The same approach can be applied for any grade of steel or any caster machine. The main advantage of the presented approach is a small number of evaluations to reach the optimal solution and its overall versatility. A combination with GPU numerical core can also allow for the on-line real-time regulation of a real CC process.

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