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INFLUENCE OF SUBMERGED ENTRY NOZZLE ON INTERMIXED ZONE IN ROUND BLOOMS WITH A DIAMETER OF 525 MM

WPLYW WYLEWU ZANURZENIOWEGO NA STREFĘ PRZEJŚCIOWĄ W OKRĄGLYCH WLEWKACH CIĄGLYCH O ŚREDNICY 525 MM

This work compares the experimental results of nickel concentration measurements in the intermixed zone of the continuously cast round blooms with a diameter of 525 mm using two types of submerged entry nozzles (SEN) – a straight-through nozzle and one with 5-ports. Based on determination of the system and optical interface in the blooms a detailed study of concentration profiles on the bloom surface in a small radius area, on the right side and then also on a cross-section of the blooms, was carried out. The results were further analysed using approximation models, and were to be used to verify the proposed model for predicting intermixed zones for a continuous casting machine, developed based on the results of physical and numerical modelling.

Keywords: continuous casting machine, steel round bloom, submerged entry nozzle, SEN, intermixed zone, concentration profile

Praca przedstawia porównanie wyników pomiarów doświadczalnych stężenia niklu we wlewkach okrągłych o średnicy 525 mm odlewanych metodą COS z strefą przejściową, przy użyciu dwóch typów wylewów zanurzanych typu SEN – wylewu osiowego oraz promieniowego 5-strumieniowego. Pomiarów wykonano na powierzchni wlewków oraz na ich przekroju poprzecznym przy użyciu metod optycznych. Analizę uzyskanych wyników pomiarów przeprowadzono wykorzystując modele aproksymujące. Uzyskane w ten sposób rezultaty wykorzystano do modernizacji opracowanego wcześniej w oparciu o rezultaty badań o charakterze modelowania fizycznego i numerycznego modelu do prognozowania wielkości strefy przejściowej dla badanego urządzenia do ciągłego odlewania stali.

1. Introduction

When casting two different steel grades in sequence, the steels tend to get mixed in the tundish and, in certain cases, also in the liquid cores of the solidifying blanks. That leads to the emergence of chemistries that correspond neither to the previous nor to the following cast steel grade. A so-called intermixed zone occurs in the continuously cast blanks as a result, with the chemical composition out of the tolerance specified for either of the cast steel grades. Verification and minimisation of these intermixed zones is an important pre-requisite to increasing the productivity of continuous casting machines (CCM) [1, 2, 3, 4].

Currently, the Model for predicting of Intermixed Zones (MIZ), which systematically manages and identifies composite blooms resulting from the sequential casting of different steel grades with different chemical composition is being put into operation under the conditions of the 5-strand bloom, CCM No.1 in Třinecké železářny a.s. (TŽ). The similar model has been fully operational since 2005 under conditions of

the 8-strand billet, CCM No.2 [5, 6]. The model for the CCM No.1 is developed based on data received from the physical and numerical modelling [6, 7], which allowed taking into account the relevant changes in the operating boundary conditions, such as initial and final mass/weight of steel in the tundish during the refilling, the intensity (mass flow rate) of the tundish refilling, casting speed, stop of casting strands, etc. [8].

The results of model experiments were then processed using mathematical - statistical methods, with the assistance of which the regression equations of linear parameters in intermixed zones were obtained [9,10], and in the next step these were generalized for all cast formats on CCM No.1.

While implementing the MIZ to the conditions of CCM No.1 the possible penetration of new steel grade into the molten core of blooms, which can be expected, especially when utilizing straight-through SENs with a highly dynamic effect of a molten steel stream, as well as in the case of larger formats of cast blooms, needed to be taken into account [11].

In order to clarify the intensity of this penetration, sev-

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eral complex plant experiments were carried out, the result of which is obtaining the data analysing the concentration profiles on the surface and cross-sections of the blooms present in the intermixed zone.

2. Preparation and implementation of experiment

To determine a longitudinal and lateral chemical concentration profile in the round blooms of the intermixed zone, experimental methods, whose principles lie in mild alloying of two consecutive cast heats by nickel and chromium using the "cross method" and in the subsequent determination of content of these elements on the surface of the blooms, and in particular on the cross sections of these blooms, were used.

During the first test using straight-through SENs the heats were purposely alloyed to achieve the goal of 0.26 wt.% Ni and 0.26 wt.% Cr, and during the second test using 5-port SENs (complemented with the bottom fifth optimized port) to 0.27 wt.% Ni and 0.28 wt.% Cr.

Both tests have maintained the same weight of steel in the tundish at the initiation of its refilling (24 tons) and a very close intensity of the mass flow into the tundish (5.8 and 6.3 t.min⁻¹). The second test was carried out on the casting strand (CS) No.5 with an active electromagnetic stirrer of the *M-EMS* type.

To evaluate the chemical composition itself, the round blooms with a 525 mm diameter were separated from the intermixed zone of the monitored casting strands, i.e. CS No.1 and CS No.5 (first test), CS No.4, and CS No.5 (second test). After cooling, the blooms were transported into the roughing room, in which, during the first stage, the grinding of solid longitudinal surfaces on a small radius (SR) and the right side (RS) of the bloom took place to carry out spectrometric analyses across the entire length of all the evaluated blooms – see Fig. 1a.

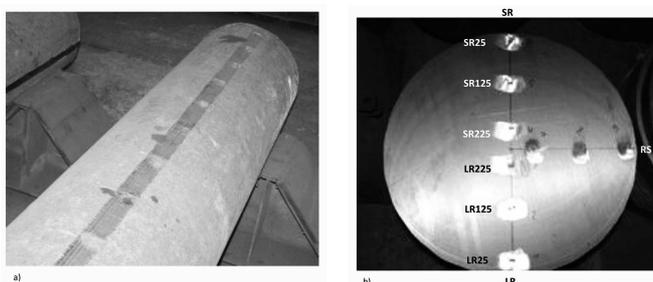


Fig. 1. Separated blooms with a 525 mm diameter after spectrographic analyses on surface (a) and cross sections (b)

After evaluating the results a cutting plan was prepared and the blooms were cut with a band saw into approximately 40 cm-long pieces (logs), and detailed analyses were carried out on the resulting cross sections in the direction from a small radius (SR) through the centre to a large radius (LR) as well as from the right side toward the centre of the bloom, a total of and in 9 locations of cross section - see Fig. 1b.

3. Results of chemical composition on the surface and cross-sections of blooms

Using the CCM No.1 operating database, detailed time data related to the cast length of the blooms, casting speed, change in the weight of steel, both in the tundish and casting ladle, have been obtained. These data were used to locate the precise location on the blooms, which correspond to the initiation time of the steel flow from the new casting ladle into the tundish. Length parameters in the appropriate charts are subsequently related to the point or location that corresponds to this change. Negative length values can signal that it concerns a bloom that has been cast (it was pulled from the mould) even before the initiation of the steel flow from the new ladle.

Given that the change in chromium content has mirrored the change in nickel content, the other parts of the paper only present the results and evaluation of changes in the nickel content. As shown Fig. 2 and Fig. 3, on the surface and cross-sections of the blooms some gradual changes in the content of nickel were detected (and similarly also converse changes to the content of chromium), which correspond to the composition of the subsequently cast heats.

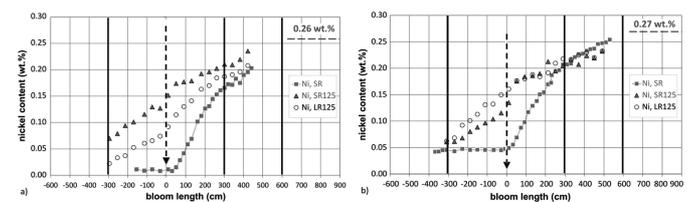


Fig. 2. Graphic illustration of variations in the content of nickel on the surface and cross sections of **CS No.5** blooms at a distance of **125 mm** from the surface of round blanks in the casts using straight-through SEN (a) and five-port SEN (b)

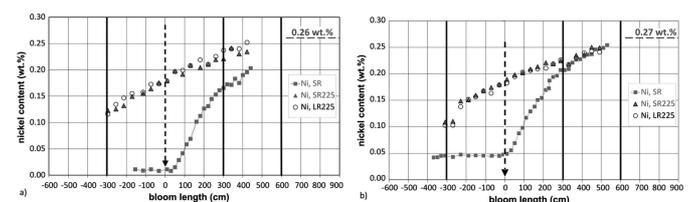


Fig. 3. Graphic illustration of variations in the content of nickel on the surface and cross sections of **CS No.5** blooms at a distance of **225 mm** from the surface of the round bloom in the heats using straight-through SEN (a) and five-port SEN (b)

In terms of individual cross-sections, a relatively high difference in chemical composition, which is caused by the reciprocal stirring of the bloom molten core with new steel coming through submerged entry nozzles, is produced.

Observed evidence resulting from complete chemical analyses (2 locations of surface and 9 locations of cross section) can then be summarized as follows:

- Surface analyses on a small radius and the right side of the given strand are practically *identical*; the concentration changes on the surface are balanced along the bloom perimeter.
- At a distance of 25 mm below the surface of the blooms, some minor differences between changes in the contents of Cr and Ni are apparent due to surface analyses. Chemical

composition is already affected by the composition of the *subsequent heat*. Changes in the composition in the area of a small radius in this case are similar to the ones on the side of a large radius.

- The chemical composition of an inside part of the bloom at the distance of *125 mm* below its surface is already completely different from its surface (Fig. 2). The penetration of "new" steel from the subsequent heat to the bloom core is significantly apparent here, which creates a characteristic concentration gradient across the cross section of the bloom. It is obvious that changes in the chemical composition inside the bloom within a distance of *125 mm* from the surface "are forerunning" surface analyses for at least **2 m**, and in some cases for more than **3 m**.
- The chemical composition of blooms at a depth of *225 mm* below the surface also exhibits significant differences compared to the bloom surface (Fig. 3). The charts can also serve to estimate, with some degree of accuracy, the penetration of liquid molten metal, and thus the reciprocal stirring for up to a distance exceeding **3 to 3.5 m** from the outlet of the five-port SEN (more than **4.5 m** for straight-through SEN).
- From the charts it can also be inferred that reaching the chemical composition of the subsequent heat in the cast blooms can be located at a distance of approximately **6-8 m** from the location that corresponds to the steel flow initiation from the new casting ladle, which is with a nominal casting speed of $0.32 \text{ m}\cdot\text{min}^{-1}$ equalled to **1125-1500 sec** (approx. 19-25 minutes).
- Mutual comparison of concentration changes courses has also led to important findings, according to which the effect of the **5-port SEN** on the concentration changes behaviour in the cross-sections of the bloom was, in comparison with a **straight-through SEN**, less significant. The radius of casting strand penetration into the molten steel core of the bloom can then be expected in case of the straight-through SEN at a distance of more than 4-5 m, and in case of the 5-port SEN at a distance of 3-4 m.
- In the case of the *straight-through SEN*, the changes in chemical composition have first shown on the side of a small radius, in the case of the *5-port nozzle* on the side of a large radius, but considerably less significantly compared to the straight-through SEN. The above described behaviour seems to be associated with the nature of the steel outflow from both types of nozzles – in the case of a *straight-through nozzle*, reverse recirculation in subsurface layers takes place more intensely on the side of a small radius due to the interaction of the outlet casting stream as well as the curvature of the mould (or the bloom's wall). On the contrary, in the case of the *5-port nozzle* a more dominant effect of the orientation of the side ports with regard to the bloom wall (i.e. settling of the bloom), but also an effect of the uneven sedimentation of the side ports etc., can be assumed.

4. Mathematical – statistical processing of measurement results

Given the fact that the performed operational experiments using straight-through and 5-port SEN were primarily intended to determine concentration profiles in the blooms and to assess the extent of the intermixed zone, or the degree of reciprocal stirring process in the molten core of the bloom with a diameter of *525 mm*, the results achieved were intended to be processed using an *appropriate approximation model*.

In the period following the start of filling the tundish by a new steel grade with different composition, a response to changes in concentrations of chemical elements at the outputs of the tundish is characterized by a certain dependence, which corresponds to the so-called *transition curve* (its characteristics), and which is a graphical representation of the so-called transition function.

In the calculations, length (not time) parameters of the blooms were considered, which were related to the location of the so-called "optical" interface, i.e., location that corresponds to the *start of filling the tundish with steel from another ladle* with a different chemical composition.

Results of concentration measurements were first *standardized* to the dimensionless concentration c_n , taking into account values of the average (specified) element content.

For an approximation of these concentration processes, a proportional system of the *first order with time delay and amplification unit* was selected. Its *transition characteristics* (as a response to a unit step of change in the mass content of alloying elements) with respect to the *length parameters* (the shape of the model is the same as for the time parameters; the length parameters can be derived from the time parameters using a simple linear transformation $L_x = v \times T_x$, where v is the casting speed) is as follows:

$$c_{an}(l) = \begin{cases} 0 & \text{pro } l \leq L_d \\ 1 - \exp\left(-\frac{l-L_d}{L_1}\right) & \text{pro } l > L_d \end{cases} \quad (-) \quad (1)$$

where:

c_{an} – approximated standardized concentration of the element in steel $\in (0,1)$ (-)

l – bloom length (m)

L_d – (transport) length delay (m)

L_1 – system length constant (m)

Fig. 4 and Fig. 5 show the graphic illustration of the results of this approximation for surface analyses and at the distance of *125 mm* from the bloom surface.

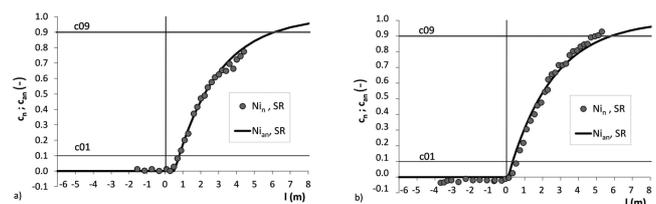


Fig. 4. Approximation of Ni concentration variations on SR surface of CS No.5, for straight-through (a) and five-port SEN (b)

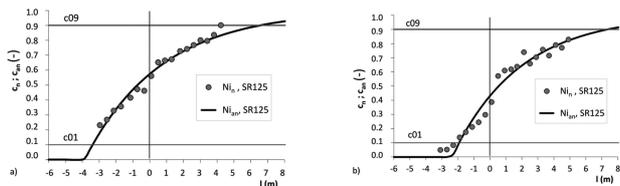


Fig. 5. Approximation of Ni concentration variations on cross sections of CS No.5 blooms at a distance of 125 mm from the surface SR for straight-through (a) and five-port SEN (b)

In the next step, an appropriate, simple (with the lowest number of parameters and from a set of basic functions), non-linear approximate-regression function of the dependence of calculated L_d on h (distance from surface of round bloom) was searched. An appropriate one seems to be an exponential function with a (absolute) shift of values (which often represents a solution to common equations, but in the proximity even to partial differential equations) in the following form:

$$L_{da}(h) = a + b \cdot \exp(c \cdot h) \quad (m) \quad (2)$$

This function serves to estimate the penetration of “new” steel into the bloom core (the centre, or the longitudinal axis) with “old” steel. The results for both, *straight-through and 5-port nozzles* are listed in Table 1, Table 2 and Table 3, where:

- $h \dots$ distance from the surface of the round bloom
- $L_{da} \dots$ approximation of L_d using nonlinear regression dependence of L_d on h
- $l(0.1) \dots$ length of the beginning of the intermixed zone for the lower boundary of the concentration $c_{n,min} = 0.1$
- $l(0.9) \dots$ length of the end of the intermixed zone for the upper boundary of the concentration $c_{n,max} = 0.9$
- $l_S(0.1,0.9) \dots$ length of the intermixed zone between the lower and upper boundary of the standard concentration $c_m = \{0.1, 0.9\}$

TABLE 1

Parameters of new steel penetration into the bloom molten core dia.525 mm for CS No.5 using *straight-through SEN*

Name	SR	SR25	SR125	SR225	Centre
h (mm)	0	25	125	225	262.5
L_d (m)	0.546	-0.516	-3.860	-5.238	—
L_1 (m)	2.413	2.395	4.528	4.452	—
L_{da} (m)	0.614	-0.626	-3.786	-5.270	-5.594
$l(0.1)$ (m)	0.800	-0.264	-3.383	-4.768	—
$l(0.9)$ (m)	6.102	4.998	6.565	5.013	—
$l_S(0.1,0.9)$ (m)	5.302	5.262	9.948	9.782	—

From the tables listed above it is apparent that the relatively smallest *depth of penetration* of the new steel into a body of the bloom was achieved in CS No.4 when utilizing a 5-port nozzle, and it was approximately 3.9 m.

It has been found that in CS No.5 with the *M-EMS* was increased of depth of penetration of the “new” steel into the core (centre) of the “old” bloom for up to approx. 1.4 m (for

approx. 36 %) compared with CS No.4. However, it cannot be unequivocally stated that this is the effect of electromagnetic stirring of the *M-EMS* type. The role can, for example, have clogging of the lower (fifth) output port from the SEN, and an associated effect of lower dynamic effect of the out-flowing steel stream etc.

TABLE 2

Parameters of new steel penetration into the bloom molten core dia.525 mm for CS No.4 using *five port SEN*

Name	SR	SR25	SR125	SR225	Centre
h (mm)	0	25	125	225	262.5
L_d (m)	-0.213	-0.301	-2.979	-3.548	—
L_1 (m)	1.822	2.588	4.798	4.242	—
L_{da} (m)	0.048	-0.718	-2.704	-3.666	-3.881
$l(0.1)$ (m)	-0.021	-0.028	-2.474	-3.101	—
$l(0.9)$ (m)	3.984	5.660	8.069	6.219	—
$l_S(0.1,0.9)$ (m)	4.004	5.687	10.543	9.320	—

TABLE 3

Parameters of new steel penetration into bloom molten core dia. 525 mm for CS No.5 using *five port SEN* and electromagnetic stirrer (M-EMS)

Name	SR	SR25	SR125	SR225	Centre
h (mm)	0	25	125	225	262.5
L_d (m)	0.069	-0.402	-2.371	-4.618	—
L_1 (m)	2.501	3.411	4.227	4.704	—
L_{da} (m)	0.129	-0.405	-2.504	-4.541	-5.290
$l(0.1)$ (m)	0.333	-0.042	-1.925	-4.122	—
$l(0.9)$ (m)	5.828	7.453	7.362	6.215	—
$l_S(0.1,0.9)$ (m)	5.495	7.495	9.287	10.337	—

The greatest value of the penetration depth of new steel was detected when using the *straight-through SEN*. In the central part of the bloom and based on the analyses this value was set to be 5.6 m.

The measurements performed earlier on the blooms with a diameter of 410 mm using *5-port nozzles* showed that the *depth of penetration* of the strand into the bloom core was approx. 1.7 m, which is more than twice the lesser value than the blooms with a diameter of 525 mm [12].

It has also been determined that there is a more balanced composition of steel in the rated zone in the CS No.5 bloom than in the case of CS No.4, which resulted in a certain “linearization” of the dependent courses of length parameters (see Fig. 7 for parameters such as L_d) in the intermixed zone following the bloom cross-section (which were significantly nonlinear in CS No.4 - see Fig. 6).

In addition to linearization it is also possible to monitor both a decrease in dispersion and the length values of the end of the intermixed zone ($l(0.9)$), and total length of the intermixed zone ($l(0.1,0.9)$) while considering the entire cross-section.

It can be concluded that *the position of the intermixed zone end* in CS No.4 (without *M-EMS*) ranged from approx. $4\div 8$ m (variation range approx. 4 m), while in CS No.5 (with *M-EMS*) it was approx. $6\div 7.5$ m (variation range only approx. 1.5 m). Therefore, there is a shortening of the end of intermixed zone of approx. 0.5 m.

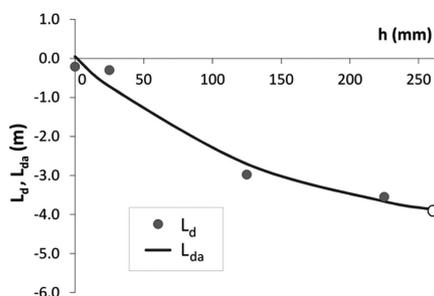


Fig. 6. Approximative dependence of L_d on h for CS No.4, small radius, 5-port SEN

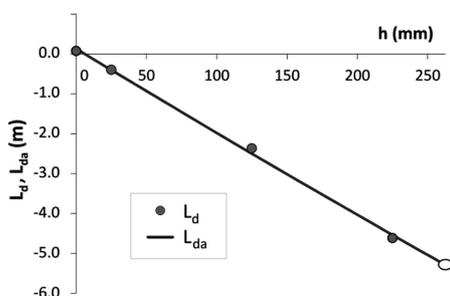


Fig. 7. Approximative dependence of L_d on h for CS No.5 (with *M-EMS*), 5-port SEN, small radius

Similarly, the *total length of intermixed zone* ranged in CS No.4 from approx. $4\div 11$ m (variation range approx. 7 m), while in CS No.5 (with *M-EMS*) it was approx. $6\div 10$ m (variation range only approx. 4 m). In this case, the shortening of intermixed zone reaches approx. 1 m.

5. Conclusion

Complex plant experiments focused on determining the concentration profiles in both the longitudinal and cross-section direction of the mixed blooms, with a diameter of 525 mm, allowed determination of the depth of penetration of new steel into the molten core of such blooms for two basic types of the used *submerged entry nozzles*: *straight-through SEN* and *combined 5-port SEN*.

The depth of penetration of the new steel into the bloom core will depend not only on the *type of SEN*, or on the *electromagnetic stirring*, but also and quite distinctively on the *cast profile*.

The greatest value of the penetration depth of new steel was detected when using the *straight-through SEN*. In the central part of the bloom and based on the analyses this value was set to be 5.6 m.

Acknowledgements

This paper was created in the project No. CZ.1.05/2.1.00/01.0040 "Regional Materials Science and Technology Centre within the frame of the operation programme "Research and Development for Innovations" financed by the Structural Funds and from the state budget of the Czech Republic.

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