ANALYSIS OF BREAKOUT OF CONCAST STEEL SLAB VIA CRITERIA OF SIMILARITY

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Abstract
The so called secondary cooling zone is an important part of the CCM. In this zone a breakout may occur due to an increase of the local and temperature heterogeneity of steel, due to an increase of the stress caused by bending of the slab and by high local concentration of non-metallic slag inclusions. Changes of the chemical composition of the steel during continuous casting are particularly dangerous. In the event that two melts are cast one right after another, i.e. if the melt of the steel with chemical composition A ends and it is immediately followed by the steel B, it may automatically stop the CCM and an atypical breakout may take place. With use of dimensional analysis altogether 8 criteria of similarity were derived according to the $\pi$-theorem. Important data in temperature field of the slab were calculated by the original model. Numerical values of eight criteria were determined for the steels A and B. This application of the theory of physical similarity clearly proved markedly increased tendency of the steel B to breakouts in comparison with the steel A. In order to prevent repetition of this accident of caster for another pair of steels cast immediately one after another, it is necessary to assess the derived individual criteria of similarity for both steels and other operations with these criteria. The way to reduce the risk of breakouts may be found mainly in the change of thermo-physical properties of both steels, consisting primarily of reduction of differences of their chemical composition.

Keywords: concast slab, chemical composition, heterogeneity, breakout

1. INTRODUCTION
Oscillation marks are transverse grooves forming on the surface of the solidifying shell of continuously cast slab. The formation of the marks is sometimes the result of bending of the solidifying shell during the oscillation of the mould \cite{1}. The hooks are solidified microscopically thin surface layers of steel. Their microstructure is different to from that of the base material of the solidifying shell. The shapes of the hooks follow the curvature of the meniscus of the solidifying steel inside the mould and they are covered with oxides and slag from casting powder. Formation of the oscillation marks is conditioned by the oscillation movement of the mould, especially by the frequency of its oscillation $f$ (i.e. the oscillation cycle), the amplitude $\Delta S$ and the casting speed $w$, which determines the speed of the movement of the slab. A significant role here is played by the negative strip time \cite{2,3}. Formation of the hooks is related to the rate of solidification of the melt and to the possibility of its flow – in the area of the meniscus – over the surface of the slab, which is roughened by the oscillation marks \cite{4}. The depth of the oscillation marks and also the shape, size and the microstructure of the hooks vary irregularly. An increasing extent of these changes leads to a defect in the shape of a crack, which reduces the thickness of the solidified shell of the slab at its exit from the mould and causes a dangerous notch. In the zone of secondary cooling, where the slab is beginning to straighten – under especially unfavourable conditions – the breakout of the steel can occur at the points of increased local chemical and temperature heterogeneity of the steel, from the increased tension as a result of the bending of the slab and also due to high local concentration of non-metallic slag inclusions. The changes of the chemical composition of the steel during the actual casting process are particularly
dangerous. The consequences of this operational immediate change of the chemical composition of the steel, which are not prevented by an anti-breakout system directly inside the mould, could lead to immediate interruption of the casting process and to a breakout at a greater distance from the mould than usual, thus leading to significant material loss and downtime.

2. **Occurrence of atypical breakout and stopping of the casting machine**

This case was recorded during the process of continuous casting of steel slabs with dimensions 250×1530 mm of the grade A with a contents (in wt.%) of C=0.416, Cr=0.95, Ni=0.03, Mn=0.7, Mo=0.206, Si=0.28 (melts 1 to 3) and the grade B with contents of C=0.174, Cr=0.07, Ni=0.02, Mn=1.46, Mo=0.005, Si=0.23 (melt 4). Casting of the first two heats of the grade A took place without any significant problems, after casting of the third melt of the grade A the fourth melt of the grade B followed. The change of the chemical compositions of the steels of both qualities was realised very quickly by changing the tundish. Inside the mould, the steel grade B mixed with the steel grade A from the previous melt. The casting continued for another 20 minutes but then at the point of start of the slab straightening at the distance of 14.15 m away from the level of the melt inside the mould, a breakout occurred between the 7th and 8th segments and the caster stopped [5]. The difference in height between the level inside the mould and the point of breakout was 8.605 m. This tear in the shell occurred on the small radius of the caster. A plate with the thickness 250 mm was taken from the breakout area using a longitudinal axial cut (Fig. 1).

3. **Application of theory of physical similarity**

The aim of this study is to clarify, which of the two steels A or B was more significantly involved in the described atypical breakout at the place of slab straightening. The susceptibility of both steels to breakouts can be analysed in two ways:

a) firstly to check, whether it is possible in the first approximation to assess even only semi-quantitatively the nature of mixing of the steels A and B, or extent of such mixing;

b) to assess qualitatively, or at least semi-quantitatively, whether it is possible to obtain with use of dimensionless criteria of physical similarity a basic idea of the relations between dimensional quantities characterising the composition of both A and B steel grades and their susceptibility to breakouts; the condition is to have in accordance with the applicable theorems sufficient necessary, but also reasonably precise, physico-chemical measurements for calculation of the needed similarity criteria.

The first way was semi-quantitatively verified and detailed information about it was published in the works [6, 7]. Mass balance analysis showed that during these 20 minutes of casting before stopping the machine the melt contained at the point of breakout approx. 25% of the steel A and 75% of the steel B with the standard deviation of 10%. It is necessary to make a data table for the way b), containing technological, geometrical, physical and chemical dimensional quantities that characterise both steel grades A and B and process of their continuous casting (Table 1). The data in the lines 11 to 17 were determined by triple calculation of temperature field of the slabs with the chemical composition A, composition B, and mixed composition A + B [8]. Thermo-physical properties of the mixed composition of the steel were determined using the IDS software according to the average chemical composition of the steels A and B [9].
ed B, in which it will be presumed that criterion is complex and it is a function of altogether seven parameters, out of \( f, T \) pairs of

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>Steel A</th>
<th>Steel B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting speed</td>
<td>( w )</td>
<td>([\text{m.s}^{-1}])</td>
<td>0.0130</td>
<td>0.0126</td>
</tr>
</tbody>
</table>
| Kinematic viscosity                            | \( \nu \) | \([\text{m}^2\text{s}^{-1}]\) | 8.706 \(10^4 \) | 7.917 \(10^4 \)
| Density                                        | \( \rho \) | \([\text{kg.m}^{-3}]\) | 7560.7           | 7600.9           |
| Latent heat of the phase change                | \( L \) | \([\text{m.s}^{-1}]\) | 246.10^-6        | 259.10^-6        |
| Specific heat capacity                         | \( c_p \) | \([\text{m}^2\text{s}^{-1}\text{K}^{-1}]\) | 632.6            | 611.0            |
| Mould oscillation amplitude                    | \( \Delta S \) | \([\text{m}]\) | 0.006±0.003      | 0.006±0.003      |
| Oscillation frequency                          | \( f \) | \([\text{s}^{-1}]\) | 1.533            | 1.533            |
| Solidus temperature                            | \( T_S \) | \([\text{°C}]\) | 1427.0           | 1480.6           |
| Liquidus temperature                           | \( T_L \) | \([\text{°C}]\) | 1700.15          | 1753.75          |
| Difference between the liquidus and solidus    | \( t_L - t_S \) | \([\text{°C}]\) | 66.9             | 31.7             |
| Max. length of the iso-solidus curve from the  | \( h_S^{\max} \) | \([\text{m}]\) | 21.07            | 19.72            |
| level (breakout)                               | \( h_L^{\max} \) | \([\text{m}]\) | 14.50            | 16.20            |
| Mn. length of the iso-solidus curve from the    | \( h_S^{\min} \) | \([\text{m}]\) | 19.92            | 18.69            |
| level (breakout)                               | \( h_L^{\min} \) | \([\text{m}]\) | 13.70            | 15.20            |
| Mn. length of the iso-liquidus curve from the   | \( F_{\text{mushy}} \) | \([\text{m}^2]\) | 0.05366          | 0.04100          |
| level (breakout)                               | \( F_{\text{slab}} \) | \([\text{m}^2]\) | 0.19125          | 0.19125          |
| The area of the mushy zone on half of the cross- | \( F_{\text{melt}} \) | \([\text{m}^2]\) | 1.381.10^-3      | 13.720.10^-3     |

Dimensional variables associated with continuous casting of steel slabs can be expressed in the first approximation in the required number together with their basic dimensions. In the case of breakout we do not know more detailed information about the internal relationship between dimensional quantities and the essence of the breakout, and we do not have either even partial mathematical and physical description of this phenomenon. That’s why it is necessary to use at application of the theory of similarity the dimensional analysis for determination of the dimensionless criteria. In accordance with the International System of Units (SI) the basic units meter-kilogram-second-Kelvin were used for expression of dimensional parameters. In our case for \( n = 12 \) dimensional quantities (Item 1-9, 15-17 in Tab.1) and for \( r = 4 \) mutually independent dimensions (M, Kg, S, K) according to the \( \pi \) theorem it makes \( 12 - 4 = 8 \) dimensionless criteria. Methods used for determination of dimensionless criteria based on the assumption of respecting the relevant theorems are described in the work [10], including the list of other recommended literature.

### 4. DIMENSIONLESS SIMILARITY CRITERIA AND THEIR CHARACTERISTICS

In accordance with the used theorems (Fourier, Buckingham, Langhaare) altogether eight necessary criteria \( \pi_1 \) - \( \pi_8 \) of physical similarity were determined for the steel grades A and B, in which it will be presumed that their increasing numerical values will characterise the susceptibility to breakouts. In the next step we will test the partial susceptibility of the relevant steel A or B to breakouts with use of shares of individual pairs of criteria. Finally, it will be decided how to attribute greater or lesser risk of breakout to one steel on the basis of both the sum and the product of all eight partial criteria determined in this manner.

\[
\pi_i = \frac{L_f}{c_p \rho v T_L \Delta S}
\]

The first criterion is complex and it is a function of altogether seven parameters, out of which four are thermo-physical properties of steel (\( L, c_p, \rho \) and \( v \)) and three are process parameters (\( f, T_L, \Delta S \)). Susceptibility to breakouts is proportional to the latent heat and inversely proportional to the product of three thermo-physical properties.
The second criterion is known as Strouhal’s criterion. Tendency to breakouts increases with the increasing amplitude of oscillation and oscillation frequency of the mould.

\[ \pi_2 = \frac{AS \cdot f}{w} \]

This criterion contains in numerator geometrical data of the mould and it is inversely proportional to kinematic viscosity.

\[ \pi_3 = \frac{AS^2 \cdot f}{\nu} \]

The fourth criterion is a function of surfaces, namely half of the cross section area of the solidified slab (i.e. \( F_{\text{slab}} = \frac{1}{2} \times 0.25 \times 1.53 \text{ m}^2 \)), of the area \( F_{\text{melt}} \) occupying half of the cross section led through the melt breakout at the temperature higher than the liquidus temperature, and the area \( F_{\text{mushy}} \) occupying half of the cross section led through the breakout solidifying melt at the temperature lying in the interval of solidification (mushy zone). Denominator \( F_{\text{slab}} - (F_{\text{melt}} + F_{\text{mushy}}) \) thus in fact reflects the current “bearing surface” of the cross section led through the breakout. Tendency to breakout increases with the decreasing denominator, i.e. with reduction of the “bearing surface”.

\[ \pi_4 = \frac{F_{\text{slab}}}{F_{\text{slab}} - (F_{\text{melt}} + F_{\text{mushy}})} \]

Simplex \( \pi_5 \) is a dimensionless temperature interval of crystallisation. This simplex must be used very carefully in cases where it is not statistically proven by higher number of melts or steels. For example in this particular case it significantly differs for both steels A and B and the steel A has greater susceptibility to breakouts.

\[ \pi_5 = \frac{T_L - T_S}{T_L} \]

Value of the complex criterion \( \pi_6 \) is directly proportional to the value of the kinematic viscosity \( \nu \) of the melt or of the mushy zone and it is inversely proportional to the oscillation frequency of the mould \( f \) and the current “bearing surface” of the section led through the breakout (as in case of the fourth criterion).

\[ \pi_6 = \frac{\nu}{f \cdot [F_{\text{slab}} - (F_{\text{mushy}} + F_{\text{melt}})]} \]

The seventh complex criterion is a function of technological parameter contained in the numerator and of thermo-physical properties contained in the denominator. Its value and thus the susceptibility to breakouts increases with the square of the speed of casting and decreases with the value of the product of the specific heat capacity and the crystallisation interval.

\[ \pi_7 = \frac{w^2}{c_p(T_L - T_S)} \]

The criterion \( \pi_8 \) in comparison with the previous one comprises also an influence of the amplitude of the mould oscillations.

5. NUMERICAL VALUES OF CRITERIA AND THEIR DISCUSSION

Numerical values of individual criteria for steels A and B are summarised in the first two rows of the Table 2.
Table 2. Assessment of influence of individual dimensionless criteria (similarity numbers)

<table>
<thead>
<tr>
<th>Criterion $\pi_i$</th>
<th>$\pi_1$</th>
<th>$\pi_2$</th>
<th>$\pi_3$</th>
<th>$\pi_4$</th>
<th>$\pi_5$</th>
<th>$\pi_6$</th>
<th>$\pi_7$</th>
<th>$\pi_8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel A $\pi_i^A$</td>
<td>8.5421</td>
<td>0.7070</td>
<td>0.06339</td>
<td>1.4041</td>
<td>0.03786</td>
<td>4.171003</td>
<td>3.991003</td>
<td>2.8251003</td>
</tr>
<tr>
<td>Steel B $\pi_i^B$</td>
<td>10.047</td>
<td>0.7300</td>
<td>0.06971</td>
<td>1.4008</td>
<td>0.01807</td>
<td>3.781003</td>
<td>8.201003</td>
<td>5.9841003</td>
</tr>
<tr>
<td>Partial share of criteria of the steels B/A: $P_i = \pi_i^B / \pi_i^A$</td>
<td>1.1762</td>
<td>1.0325</td>
<td>1.0997</td>
<td>0.9976</td>
<td>0.4772</td>
<td>0.9064</td>
<td>2.0551</td>
<td>2.1182</td>
</tr>
<tr>
<td>Progressive product of shares of criteria of the melts B/A</td>
<td>$\prod_{i=1}^{8}(P_i)$</td>
<td>1.1762</td>
<td>1.2145</td>
<td>1.3356</td>
<td>1.3324</td>
<td>0.6359</td>
<td>0.5765</td>
<td>1.1847</td>
</tr>
<tr>
<td>Partial share of criteria of the steels B/A for triple steel B in the mixture at the point of breakout</td>
<td>$P_{mix}$</td>
<td>3.5286</td>
<td>3.0976</td>
<td>3.2991</td>
<td>2.9929</td>
<td>1.4318</td>
<td>2.7194</td>
<td>6.1654</td>
</tr>
</tbody>
</table>

The 3rd row of the Tab. 2 contains the calculated partial shares of the pairs of identical criteria for the steels B and A, i.e. $P_i = \pi_i^B / \pi_i^A$. Their sum has a value $\sum_{i=1}^{8}(P_i) = 9.8632$. Average share of pairs of criteria is equal to one eighth of the sum $P_{i,mean} = 9.8632/8 = 1.2329$. Product of the shares of all eight dimensionless criteria has the value $\prod_{i=1}^{8}(P_i) = 2.5095$. Their sum has a value $\sum_{i=1}^{8}(P_{i,...,8}) = 9.9654$. Its average value is $9.9654/8 = 1.2457$. We can see that in both cases the average value of the shares, as well as the average value of the products is greater than 1. It means that the steel grade B has higher susceptibility to breakouts. It follows from Tab. 2 that partial shares $P_2$, $P_3$, $P_4$ and $P_5$ in Tab. 2 are alternating for both steels A and B around the number 1. The share $P_1$ means that criterion $\pi_1$ is in the steel B 1.18 times bigger than in the steel A, which manifests bigger susceptibility of the steel B to breakouts. Partial shares $P_7$ and $P_8$ show that criteria $\pi_7$ and $\pi_8$ are in the steel B more than twice bigger than in the steel A. This manifests a distinct tendency of the steel B to initiate breakouts. On the other hand the share $P_5$ indicates only half tendency of the steel B to breakout in comparison with the steel A. According to the $P_{i,mean} = 1.2329$ for the average share of criteria it may be stated that the steel B has at the average the susceptibility to breakouts higher by 23%. This higher susceptibility of the steel B to breakouts is manifested also by the value of the product of individual shares and by the average value of the product the 1.2457 ensuing from it. The existing assumption attributed the same initiation effect to formation of breakout to all eight dimensionless similarity criteria provided that notch at the place of the casting mark or crisp or hook (see Figs. 1) was not influenced by real mass share of each steel at the point of breakout, but by their thermo-physical and chemical properties. It followed from the balance analysis [6] that as a result of mixing of melts of both steels the mass share of the steel A was at the place of breakout approx. 25% and that of the steel B was approx. 75%. So, we can express the susceptibility of the given steel to breakouts by the product of the relevant criterion and mass share of the steel. For example for the first criterion the product has the value $\pi_1^A \times 0.25 = 2.135$ and for the steel B $\pi_1^B \times 0.75 = 5.7535$. Partial share of the first criteria for the mixture A+B is determined as $P_{mix} = 7.535/2.135 = 3.529$. Risk of breakout of the steel B is 3.529 times higher than that of the steel A. It follows from the mass share of the steels A and B in the breakout (i.e. $0.75/0.25 = 3$) that $P_{mix} = 3P_1$, where $P_i$ are the values from the 3rd row of the Table 2. We will now enter into the last row of the Table 2 partial shares of all criteria $P_{mix}$. The increased susceptibility of
the steel B to breakouts in comparison with the steel A is according to these values of $P_{\text{mix}}$ absolutely evident, even for the 5th criterion ($P_{\text{mix}} = 1.4318$), in which value the of simple partial share of criteria indicated even the opposite tendency ($P_{5} = 0.4772$). The sum $\sum_{i=1}^{5} P_{\text{mix}}$ is 29.590 and the average value of the share $P_{\text{mix}}^{\text{mean}} = 3.6987$ is a triple of the value $P_{\text{mean}}$. However, these values can be considered only as preliminary ones until we know the mass share of both steels in the breakout more precisely. Progressive product of the shares $P_{\text{mix}}$ was not calculated anymore.

6. CONCLUSIONS

An analysis performed with use of the similarity criteria clearly demonstrates objectively significantly increased susceptibility of the steel B to breakouts in comparison with the steel A. If it is impossible to change the technological and geometrical quantities entering into the individual criteria, then it is necessary that remaining 12 quantities of both steels differ as little as possible, particularly thermo-physical properties, which vary with the chemical composition of the steel. From this perspective, the decisive criteria are the first ($\pi_1$), seventh ($\pi_7$) and eighth ($\pi_8$), which are a function of altogether six thermo-physical properties, namely latent heat of phase transformation, specific heat capacity, density, kinematic viscosity, liquidus and solidus temperatures, or their difference. The seventh and eighth criteria are functions of casting speed, which means that their reduction would reduce the risk of breakout. When selecting two steels, which must be cast on the continuous casting machine consecutively one after another, the technologist should therefore follow the value of partial shares of the first, seventh and eighth criteria $P_1$, $P_7$ and $P_8$. He will not have at his disposal more conclusive shares $P_{\text{mix}}$, $P_{7\text{mix}}$ and $P_{8\text{mix}}$, because he will not know the real mass shares of both steels at the place of potential breakout, nor position of the breakout, as was the case of the steels A and B discussed here.

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