UDK 621.74.047:669.14.018
Professional article/Strokovni članek

ISSN 1580-2949
MTAEC9, 45(6)599(2011)

THE EFFECT OF ELECTROMAGNETIC STIRRING ON THE CRYSTALLIZATION OF CONCAST BILLETS – II.

VPLIV ELEKTROMAGNETNEGA MEŠANJA NA KRISTALIZACIJO KONTINUIRNO ULITIH GREDIC – II.

Frantisek Kavicka[1], Karel Stransky[1], Bohumil Sekanina[1], Josef Stetina[1], Vasilij Gontarev[2], Tomas Mauder[1], Milos Masarik[3]

[1]Brno Technological University, Technicka 2, 616 69 Brno, Czech Rep.
[2]University of Ljubljana, Aškerčeva 12, 1000 Ljubljana, Slovenia
[3]EVRAZ VITKOVICE STEEL, a. s., Stramberska 2871/47, 709 00 Ostrava, Czech Rep.
kavicka@fme.vutbr.cz

Prejem rokopisa – received:2011-02-01 ; sprejem za objavo – accepted for publicatio: 2011-03-03

The solidification and cooling of a continuously cast slab and the simultaneous heating of the mold is a very complicated problem of three-dimensional (3D) transient heat and mass transfer. The solving of such a problem is impossible without numerical models of the temperature field of the concasting processed through the concasting machine. Experimental research and measurements have to take place simultaneously with the numerical computation, to be confronted with the numerical model and make it more accurate throughout the process. An important area of the caster is the secondary cooling zone, which is subdivided into thirteen sections. In this zone, where the slab is beginning to straighten, the breakout of the shell can occur at points of increased local chemical and temperature heterogeneity for the steel, from increased tension as a result of the bending of the slab and also from a high local concentration of non-metal and slag inclusions. The changes in the chemical composition of the steel during the actual concasting are particularly dangerous. In the case of two melts, one immediately after the other, this could lead to an immediate interruption in the concasting and a breakout. The material, physical, chemical and technological parameters, which differed in both melts, were determined. If the dimensionless analysis is applied for assessing and reducing the number of these parameters, then it is possible to express the level of risk of the breakout as a function of five dimensionless criteria.

Keywords: concast slabs, oscillation marks, hooks, chemical composition, breakout, criteria, electromagnetic stirring, crystallization

Strjevanje in ohlajevanje kontinuirno ulitega slaba in istočasno ogrevanje kokile je zelo zapleten problem pri tridimenzionalnem (3D) prenosu toplote in mase. Rešitev takega problema je nemogoča brez uporabe numeričnih modelov temperaturnega polja pri kontinuirnem ulivanju. Eksperimentalne raziskave in meritve se morajo dogajati istočasno z numeričnim računom, ne le zaradi primerjave z numeričnim modelom, ampak tudi zaradi večje natančnosti samega procesa. Pomembno področje livnega stroja je t. i. sekundarna hladilna cona, ki je razdeljena v trinajst presekov. V sekundarni hladilni coni lahko nastane preboj skorje zaradi povečane lokalne kemijske in temperaturne heterogenosti jekla, porasta napetosti v slabu zaradi upogibanja in velikih lokalnih koncentracij nekovinskih vključkov in vključkov žlindre. Posebno nevarne so spremembe kemijske sestave jekla med dejanskim kontinuirnim ulivanjem. V primeru dveh talin, ki sledita ena takoj za drugo, lahko nastane takojšnja prekinitve kontiulivanja in preboja. Določeni so bili fizikalni, kemijski in tehnološki parametri snovi, v katerih se obe talini razlikujeta. Z uporabo brezdimenzijske analize za ocenitev in zmanjšanje števila teh parametrov, je mogoče izraziti stopnjo tveganja preboja kot funkcijo petih brezdimenzijskih meril.

Ključne besede: kontinuirno uliti drogovi, nihajoče oznake, kemijska sestava, preboj, merila, elektromagnetno mešanje, kristalizacija

1 INTRODUCTION

Oscillation marks are transverse grooves forming on the surface of the solidifying shell of a concast slab. The course of the individual marks is rough and perpendicular to the direction of the movement of the slab. The formation of the marks is sometimes the result of the bending of the solidifying shell during the oscillation of the mould, which depends on the frequency and the amplitude of the oscillation and on the casting speed. The hooks are solidified, microscopically thin, surface layers of steel [1–3] covered with oxides and slag, and their microstructures are different to that of the solidifying shell. The formation of the oscillation marks and hooks is related. 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 upon its exit from the mould and causes a dangerous notch. In the secondary-cooling zone, where the slab is beginning to straighten out, a breakout of the steel can occur at points of increased local chemical and temperature heterogeneity of the steel, from increased tension as a result of the bending of the slab and also a high local concentration of non-metal, slag inclusions. The changes in the chemical composition of the steel during the actual concasting are particularly dangerous. The consequences of this immediate operational change in the chemical composition of the steel, which are not prevented by a breakout system directly inside the mould, could lead to an immediate interruption of the concasting and a breakout at a greater distance from the mould than usual, thus leading to a significant material loss and downtime.

2 INTERRUPTION OF CONCASTING

This case was recorded during the process of concasting of (250 × 1530) mm steel slabs of quality A with the mass fractions of carbon content 0.41 % and 9.95 % chromium content (melts 1 to 3) and quality B steel with 0.17 % carbon content and 0.70 % chromium content (melt 4). The casting of the first two melts of quality A took place without any significant problems, after the casting of the third melt of quality A, the fourth melt of quality B followed. The change in the chemical compositions of the steels of both qualities was carried out very quickly by changing the tundish. Inside the mould, steel B mixed with steel A of the previous melt. The pouring continued for another 20 min, but then, after, in the unbending point of the slab, at a distance of 14.15 m away from the level of the melt inside the mould, there occurred a breakout between the 7^{th} and 8^{th} segments and the caster stopped. The difference in the height between the level inside the mould and the breakout point was 8.605 m. This tear in the shell occurred on the small radius of the caster. A 250-mm-thick sample was taken from the breakout area using a longitudinal axial cut (**Figure. 1**). The structure of this sample was examined and using the Bauman print the distribution of sulphur was analyzed too. The numbers 1 to 11 indicate the positions of the samples in the places around the breakout intended for the analysis. Simultaneously, significant 25-mm sulphide segregations were discovered (see **Figure 1, position 6**) – very heterogeneous areas created by the original base material of the slab (melt 3), the new material of the slab (melt 4) and between them and also by the areas of mixed composition. Beneath the surface of the slab, at a depth of 75–85 mm, there were cracks and a zone of columnar crystals oriented towards the surface of the slab on the small radius. This was identical to the orientation of the groove, which gradually turned into a crack (**Figure 1 – direction 4–6**) and, on the opposite surface of the slab, the hook which was covered by the melt (position 8). In the first phase of the analyses, the aim was to determine the material, physical, chemical and technological parameters, for which both melts 3 and 4 differed (besides the already introduced chemical composition). **Table 1** contains the individual parameters of both melts.

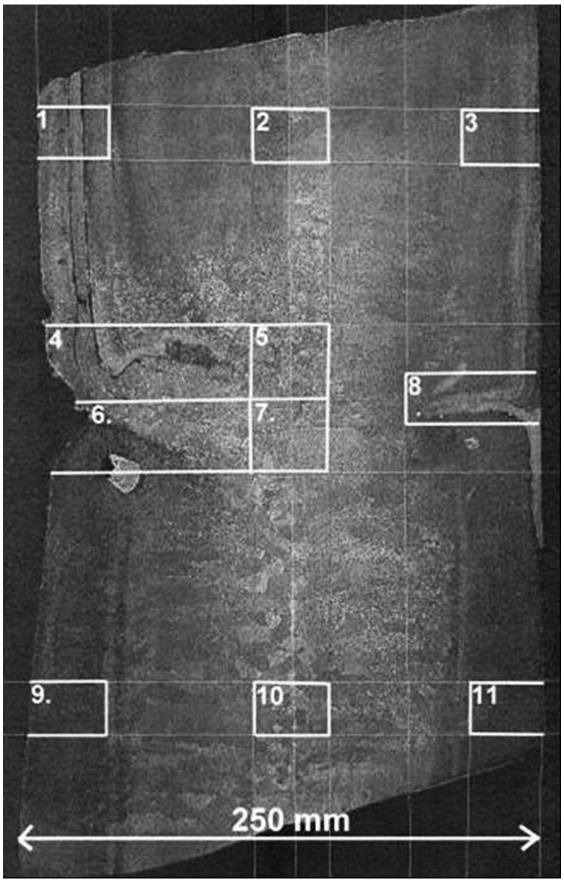

Figure1: Macrostructure of breakout
Slika 1: Makrostruktura zloma

3 DIMENSIONLESS CRITERIA

If the method of dimensionless analysis is applied for assessing and reducing the number of parameters in **Table 1** in the first approximation, then it is possible to express the level of risk of breakout as a function of the five dimensionless criteria contained in **Table 2** (units m, kg, s, K).

4 SUSCEPTIBILITY TO BREAKOUT – BREAKOUT RISK

The risk of breakout grows in accordance with the first criterion in direct proportion to the latent heat L released from the mushy zone and inversely proportionally to its dynamic viscosity η. The second criterion, i.e., the Strouhal number, includes transient, oscillation movement, including the amplitude of the mould and also, implicitly, a susceptibility to marks and hooks, which precede the breakout. The third criterion has a similar significance but, in addition, also includes the dynamic viscosity. The first three criteria increase the risk of breakout with melt 4 more than with melt 3. The fourth criterion characterizes the reduction of the load-bearing cross-section of the slab (by 28.1 % in melt 3 and by 21.4 % in melt 4) by creating a mushy zone, which indicates a greater risk of breakout in melt 3. The last criterion considers the effect of the mixture zone of melt 3 and a common effect of the mixture zone of melts 3 and 4. The first three criteria are of a dynamic nature and their product in melt 3 is 1.044 × 10^6, while in the fourth melt it is 1.502 × 10^6, i.e., the mixture melt has a 50 % greater risk of breakout. The product of all five criteria of the melts 3 and 4,

Table 1: Parameters characterizing the concasting of melt 3 (quality A) and melt 4 (quality B)
Tabela 1: Parametri, ki karakterizirajo kontiulivanje taline 3 (kakovost A) in taline 4 (kakovost B)

Item #	Parameter	Symbol	Units	A – melt 3	B – melt 4
1	Pouring speed	w	m s^{-1}	0.0130	0.0126
2	Dynamic viscosity	η	m^{-1} kg s^{-1}	0.00570 T_L	0.00562 T_L
		$\eta = \rho \cdot \nu$	m^{-1} kg s^{-1}	0.00772 T_S	0.00615 T_S
3	Density	ρ	kg m^{-3}	7560.7	7600.9
4	Latent heat of the phase change	L	m^2 kg s^{-2}	246 × 10^3	259 × 10^3
5	Specific heat capacity	c_p	m^2 s^{-2} K^{-1}	632.6	611.0
6	Mould oscillation amplitude	ΔS	m	0.006 ± 0.003	0.006 ± 0.003
7	Oscillation frequency	f	s^{-1}	1.533	1.533
8	Solidus temperature	T_S	°C	1427.0	1480.6
9	Liquidus temperature	T_L	°C	1493.9	1512.3
10	Difference between the liquidus and solidus temperatures	$T_L - T_S$	°C	66.9	31.7
11	Max. length of the isosolidus curve from the level*	h_S^{max}	m	21.07	19.72
12	Min. length of the isosolidus curve from the level**	h_S^{min}	m	19.92	18.69
13	Max. length of the isoliquidus curve from the level*	h_L^{max}	m	14.50	16.20
14	Min. length of the isoliquidus curve from the level**	h_L^{min}	m	13.70	15.20
15	The area of the mushy zone on half of the cross-section of the breakout $^+$	F_{mushy}	m^2	0.05366	0.04100
16	The surface temperature of the slab^{++}	T_{surf}	°C	934	1097

Note (continued from table above): *) of the steel inside the mould to a position 0.650 m from the edges of the 1.53 m wide slab; **) of the steel inside the mould to the centre of the slab; $^+$) the overall area of half of the cross-section is F_{slab} = 0,19125 m^2 ; $^{++}$) in the material 15 mm around the groove (**Figure 1**). The data in Table 1 were established a) on the caster after breakout; b) from archived on-line results of the temperature model; c) by off-line modelling of the temperature field of melts 3 and 4 [5].

Table 2: Dimensionless criteria characterizing the breakout
Tabela 2: Brezdimenzijska merila, ki označujejo zlom

Criterion	$\frac{L \cdot f}{c_p \eta T_L \Delta S}$	$\frac{\Delta S \cdot f}{w}$	$\frac{\rho \Delta S^2 \cdot f}{\eta}$	$\frac{F_{slab}}{F_{slab} - F_{mushy}}$	$\frac{T_L - T_S}{T_L}$
steel A	5124.78	1.179	172.77	1.3900	0.044782
steel B	6237.96	1.217	197.87	1.2729	0.056404*

Note: *) The maximum temperature difference inside the mixture zone $(T_{L-B} - T_{S-A})/T_{L-B}$

Table 3: Ductility testing at 1093.0 °C and 914.5 °C [5]
Tabela 3: Preizkusi gnetljivosti pri 1093.0 °C in 914.5 °C [5]

Sample	Testing temperature	Tensile strength	Strength	Diameter	Contraction	Deformation before breaking	Breaking Work
	°C	N	MPa	mm	%	mm	J
1	1093	817	28.9	3.90	58.0	12.0	7
2	914.5	1247	44.1	5.35	21.5	5.5	6

considering their partial homogenization, is 1.078 × 10^5 in melt 4 and 6.498 × 10^4 in melt 3. The quotient of the product for melts 3 and 4 is 0.603, which predicts a reduced risk of breakout in melt 3. If the influence of temperature on the surface of the slab in melt 3 and in the place of the groove in melt 4, it is clear that the effect of the groove during the straightening out of the slab is connected with the tensile stress, then in the place of the groove (**Figure 1**) the effect must have been compensated for at a temperature of 1097 °C, i.e., at a temperature that is 163 °C higher than that of a completely straight surface of the slab of melt 3. The data was obtained from the investigation into the causes behind a transversal crack that occurred in a different steel slab [4].

In order to clarify this, it was necessary to conduct a series of ductility tests at temperatures ranging from 20 °C to the solidus temperature. **Table 3** contains the test results from temperatures that are close to the temperatures in row 16 of **Table 2**. A comparison of the mechanical values indicates that the tensile strength at 914.5 °C and the pulling force are 1.5 times greater than at 1093.0 °C. In addition to this, there was a 8 605 m column of melt working on the mushy zone at the point of the breakout, where the mushy zone reached h_S^{max} = 21.07 m from the level in the mould, i.e., at least 6.92 m beyond the breakout point. It is therefore possible to assume that the main factor that significantly increased the risk of breakout was the superposition of the causing effects of the parameters occurring in the first four criteria of **Table 2**.

5 DISCUSSION

Following a rapid change of the tundish, there was a period of 20 min when there was a mixture of quality A and quality B steels. The liquidus temperature 1493.9 °C of quality A increased to 1512.3 °C and, simultaneously, the latent heat of the phase change increased from 246 kJ/kg (quality A) to 259 kJ/kg (quality B). This led to an increase in the temperature of the melt and to the re-melting of the solidified shell of the original quality A steel. Furthermore, there was an increase in the length of the mushy zone (up to $h^{\max}_{S-3t.melt} - h^{\min}_{S-3.melt}$ = 21.07 – 13.70 = 7.37 m) and also in its temperature heterogeneity. The temperature of the mushy zone – following the mixing of both qualities – could find itself anywhere between the maximum temperature of the liquidus of quality A and the minimum temperature of the solidus of quality B (i.e., within the interval $T_{L-B} - T_{S-A}$= 1512.3 – 1427.0 = 85.3 °C. During the 20 min of pouring of the quality B steel (the 4th melt), which began immediately after the quality A steel (the 3rd melt), marks and hooks formed as a result of the oscillation of the mould and continued to form during the unbending of the slab (**Figure 1** – where the groove is 50 mm wide and 15–16 mm deep with an opening angle of 115°). The tensile forces in the vicinity of this groove and the re-melting of the solidified shell brought about the breakout in the wall of the small radius of the slab in the unbending point.

6 CONCLUSION

The changes in the chemical composition of the steel during the actual concasting are particularly dangerous. One way of reducing the risk of breakout and the consequent shutdown of the caster is to modify the values of the dimensionless criteria characterizing the breakout, i.e., to select two consecutive melts of such chemical compositions and the corresponding physical and chemical parameters (from which the dimensionless criteria are determined) that the criteria predict zero-breakthrough.

Acknowledgements

GACR projects No. 106/08/0606, 106/09/0940, 106/09/0969 and P107/11/1566.

7 REFERENCES

[1] Badri A. et al.: A mold simulator for continuous casting of steel. part ii. the formation of oscillation marks during the continuous casting of low carbon steel. Metallurgical and Materials Transactions B, 36 (**2005**), 373–383

[2] Thomas, B. G., J. Sengupta, Ojeda, C. Mechanism of hook and oscillation mark formation in ultra-low carbon steel. In Second Baosteel Biennial Conference, (May 25–26, 2006, Shanghai, PRC), 1 (**2006**), 112–117

[3] Ojeda, C. et al.: Mathematical modeling of thermal-fluid flow in the meniscus region during an oscillation cycle. AISTech Proceedings, 1 (**2006**), 1017–1028

[4] Dobrovska, J. et al.: Analysis of a transversal crack in a steel slab. Materials Science Forum, 567–568 (**2007**), 105–108 ©2008 Trans Tech Publications, Switzerland

[5] Stetina, J. et al.: Optimization of a casting technology of a steel slab via numerical models. Proceedings 22nd Canadian Congress of Applied Mechanics, Dalhousie University Halifax, Nova Scotia, Canada, May **2009**, 4