APPLYING MOULDSCREEN® IN THE INDUSTRY, FIRST TRIAL RUNS OF A NEW FLUX FILM VISUALIZATION TOOL AT A SLAB CASTER[1]

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Abstract

The behaviour of the flux film between strand shell and mould plate is crucial for product quality, operational safety and productivity in continuous casting. Correlations between the properties of different steel grades and the different design characteristics of continuous casting machines on the one hand, and the physio-chemical properties of different mould powders and the subsequent flux film formation on the other hand are subjects of this work. Based on extensive scientific studies and in cooperation with the Department of Ferrous Metallurgy, RWTH Aachen; S&B Industrial Minerals GmbH developed a software tool that visualizes the thickness and the condition of the flux film over the entire mould area under consideration of real operation parameters. With the knowledge about certain slag properties, MouldScreen® calculates and visualizes the solid and liquid fraction of the flux film and the thickness and temperature of the strand shell and displays it on the screen. The underlying physical-mathematical model provides all relevant information about the process status in the mould (e.g. heat flux densities, strand temperature and copper plate temperature). Thermocouple readings will be included in the calculation. In addition, the MouldScreen® "Modify Tool" facilitates a detailed analysis of different key operating parameters on the flux film behaviour and thus on the lubrication and heat removal conditions between strand and mould. This function allows simulating the possible impact of any change in key operation parameters. This paper describes the results of the first application of the system to a slab caster in Germany.

Key words: Continuous casting; Mould lubrication; Flux film visualization.

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1 INTRODUCTION

With the help of a new development tool, the computer algebra (CA),(1-7) previously hardly controllable mathematical approaches for modelling the continuous casting process are now possible and can be implemented into application programs. S&B Industrial Minerals GmbH developed a software package, based on a CA algorithm in order to visualise the flux film thickness and condition between strand shell and copper plate. The program, called MouldScreen®, differentiates between liquid, mushy, and solid slag in the mould. It visualises in addition to the flux film thickness all essential information, such as shell thickness, local heat flux or the copper plate temperature as a function of position. Data acquisition is possible by manual input; by Excel spread sheets, ibaAnalyzer (data analysis software by iba AG/Germany), or online transmission. A special advantage of the MouldScreen® program is its easy application for parameter studies and inverse modelling. The present work considers shell thickness, integral and local heat flux at the meniscus and heat transfer resistance in the casting gap at the meniscus as a function of casting speed. Unfavourable conditions in the mould, leading to cracking, breakouts or other quality problems as well as system malfunctions are detected and visualised. The statistical collection and analysis of "good" (safe) and “bad” (unsafe) conditions via MouldScreen® provides future control of continuous casting machines under the additional criterion of flux film properties. Identifying critical operating conditions in the mould in real-time allowing prompt and targeted countermeasures for better and safer casting will be possible.

2 BASIC PRINCIPLES

Up to date the slag film thickness between strand and mould plate could only be predicted rudimentary, considering real operation parameters of continuous casting machines.

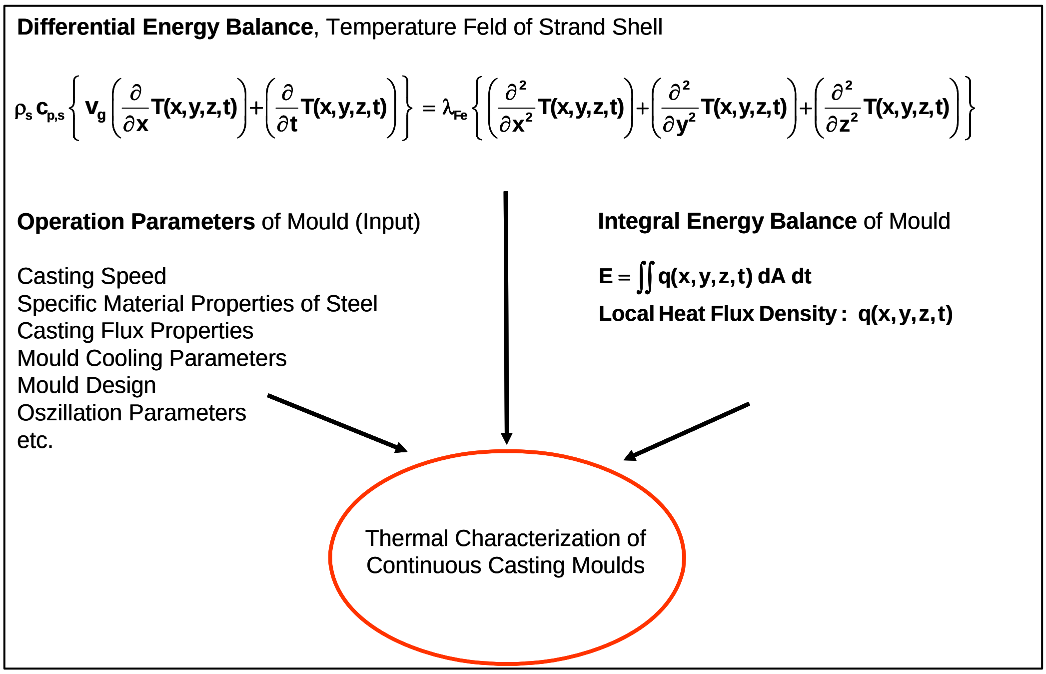


Figure 1. Basic principles and model components.

Model calculations describing a slag film, consisting of not yet measurable liquid and re-solidified casting powder layers, need to reflect the entire casting mould.

Particular attention must be given to the heat transfer within the mould slag film. Generally, such models are based on physical equations. Numerical analysis or statistics provide the disadvantages of very complex programming, overlong computing times for practical usage, and quite often results deviate from reality. Analytic solutions of the fundamental physical equations and the resulting analytical models are rather rare when it comes to continuous casting. The mathematic-physical descriptions of the thermal events inside continuous casting moulds explained in this work, present an ambitious link between differential and integral formulations of the energy theorem using real operation parameters of continuous casting machines.

Details on the formulas given in Figure 1 it is suggested to refer to literature.(1-2)

Unlike other methods, the heat transfer resistance is a direct result of the MouldScreen® algorithm. To determine the thickness of the flux film, the heat transfer resistance, described in the following as “GP” (= “Giesspulver”, German for “casting powder”), has to be multiplied by the thermal conductivity of the slag. For thermal conductivity of metallurgical slags, reference is made to the Slag Atlas.(8)

Figure 2 shows the value of GP in the area of the meniscus (GP_0) depending on casting speed. From slow casting slab machines via round billet casters to fast casting thin slab machines, the heat transfer resistance in the gap at the meniscus decreases by an order of magnitude and thus, the thickness of the flux film. With constant thermal conductivity, this means a drastic reduction of the lubricating film thickness not just at the meniscus, but also in the lower region of the mould. This is actually observed in practice: a higher casting speed means reduced mould powder consumption and this implies a lower flux film thickness.

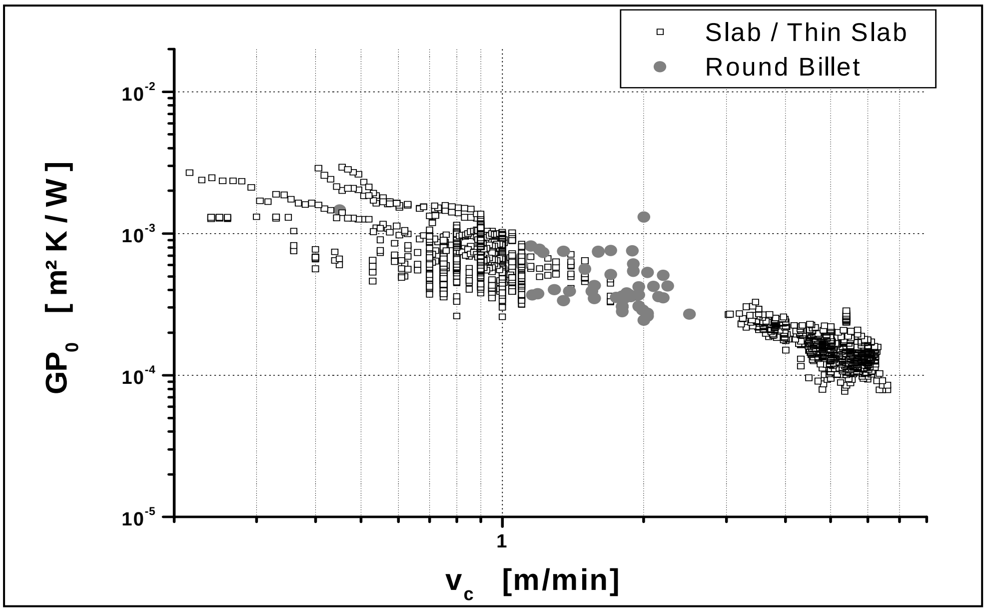
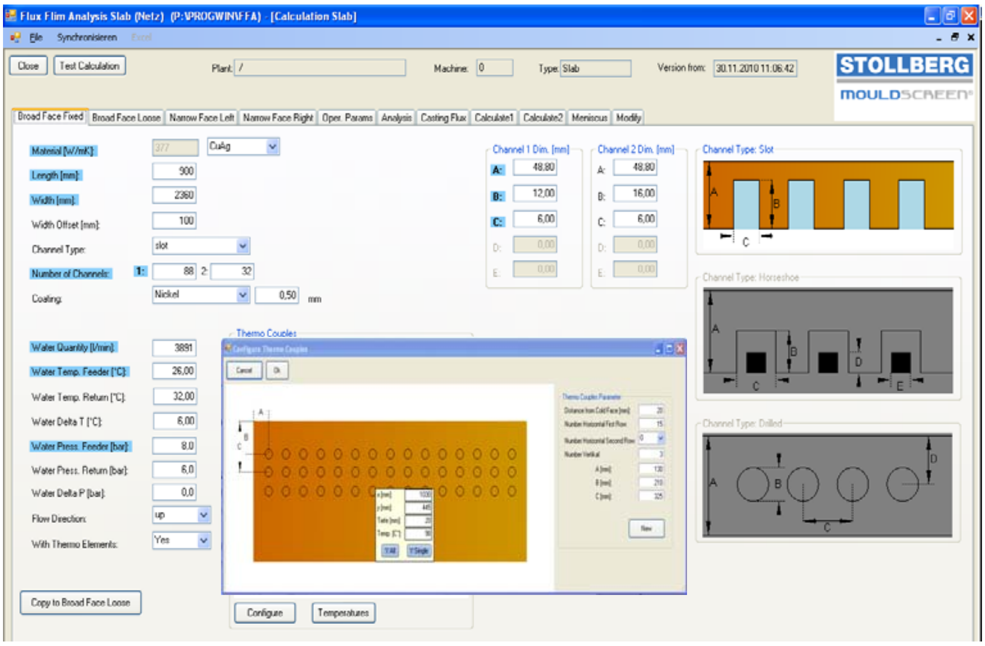


Figure 2. Heat transfer resistance of flux film at meniscus vs. casting speed, MouldScreen® evaluation.

3 THE MOULDSCREEN® SOFTWARE

With MouldScreen® the programming effort is drastically reduced. So are memory requirements and computation time of the software, both of which are smaller by an order of magnitude compared to common numerics. Other benefits are the possibilities for inverse modelling and parameter studies during online operation of the software, i.e. during data acquisition, current condition calculation and visualization.

The core idea when developing the MouldScreen® algorithm was to permanently visualize the production and quality relevant behaviour of flux film between strand surface and mould plate; considering the current casting conditions. This requires feeding the program with the characteristic mould design features, operation parameters as well as steel chemical analysis and mould flux properties.


Flux Flim Analysis Slab (Netz) (P:\PROGWIN\FFA) - [Calculation Slab]

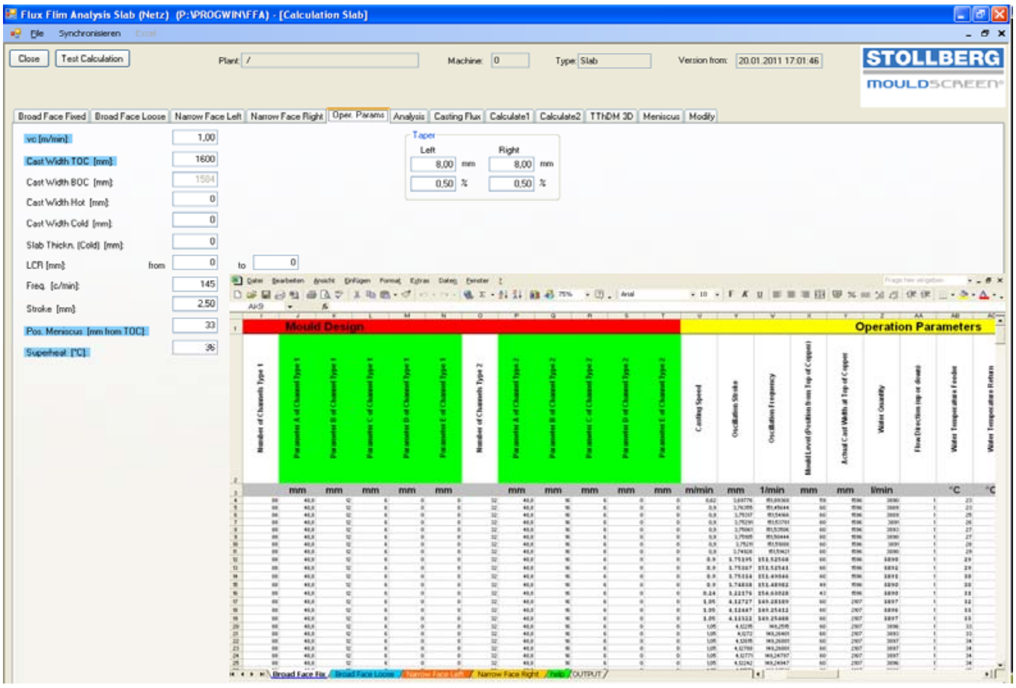
Plant: /
Machine: 0
Type: Slab
Version from: 30.11.2010 11:06:42

Material [W/mK]: 377 CuAg
Length [mm]: 900
Width [mm]: 2360
Width Offset [mm]: 100
Channel Type: slot
Number of Channels: 1: 88 2: 32
Coating: Nickel 0,50 mm
Water Quantity [l/min]: 3891
Water Temp. Feeder [°C]: 26,00
Water Temp. Return [°C]: 32,00
Water Delta T [°C]: 6,00
Water Press. Feeder [bar]: 8,0
Water Press. Return [bar]: 6,0
Water Delta P [bar]: 0,0
Flow Direction: up
With Thermo Elements: Yes

Channel 1 Dim. [mm]
A: 48,80
B: 12,00
C: 6,00
D: 0,00
E: 0,00

Channel 2 Dim. [mm]
A: 48,80
B: 16,00
C: 6,00
D: 0,00
E: 0,00

Figure 3: Data input screen: mould geometry, cooling water, thermocouples.


Flux Flim Analysis Slab (Netz) (P:\PROGWIN\FFA) - [Calculation Slab]

Plant: /
Machine: 0
Type: Slab
Version from: 20.01.2011 17:01:46

vc [m/min]: 1,00
Cast Width TOC [mm]: 1600
Cast Width BOC [mm]: 1584
Cast Width Hot [mm]: 0
Cast Width Cold [mm]: 0
Slab Thickn. (Cold) [mm]: 0
LCR [mm]: from 0 to 0
Freq. [c/min]: 145
Stroke [mm]: 2,50
Pos. Meniscus [mm from TOC]: 33
Superheat [°C]: 36

Taper
Left: 8,00 mm; 0,50 %
Right: 8,00 mm; 0,50 %

Figure 4. Data input screen: casting speed, casting width, mould level position, taper, oscillation, super heat; edited via Excel table.

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Data input can be facilitated via Excel sheets, ibaAnalyzer or online transmission. Figures 3 and 4 show some examples of the different data-input screens. After completing the data collection, the program calculates all process relevant variables, such as:

- strand shell thickness;
- local and integral heat flux density;
- water temperature inside the cooling channels/slots;
- copper plate temperatures on hot and cold sides;
- temperature field inside the strand shell;
- heat transfer resistance, condition (liquid, mushy, solid) and thickness of the slag film between strand and mould.

Immediately after setting the steel analysis and mould powder selection, the calculation results are graphically displayed in different windows. For slab and thin slab moulds, all results will be shown individually, for each copper plate by separate curves respectively graphics.

An example of the progression of the shell thickness, the local heat flux and the slab surface temperature as a function of distance from the meniscus is given in Figure 5. The corresponding curves are shown on the left side of the picture. This view considers the average numbers over the plate width. To receive values at different mould positions, small pop-up windows can be opened at any desired position in the individual graphs. Figure 5 shows an example for a position at 200 mm below meniscus. A comparison of shell thickness, local heat flux density and slab surface temperature can be easily made in this way. In the right section of Figure 5, the integral heat flux densities of the four mould plates are compared.

```
x = 0,311
s(BFF) = 0,0098
s(BFL) = 0,0120
s(NFL) = 0,0092
s(NFR) = 0,0076

sL(BFF) = 0,0199
sL(BFL) = 0,0228
sL(NFL) = 0,0192
sL(NFR) = 0,0169

x = 0,311
q(BFF) = 1,006
q(BFL) = 1,243
q(NFL) = 0,946
q(NFR) = 0,787

q0(BFF) = 1,5397
q0(BFL) = 2,6380
q0(NFL) = 1,3647
q0(NFR) = 0,9987

x = 0,311
T(BFF) = 1071
T(BFL) = 999
T(NFL) = 1092
T(NFR) = 1155

T2L(BFF) = 1002
T2L(BFL) = 957
T2L(NFL) = 1016
T2L(NFR) = 1058
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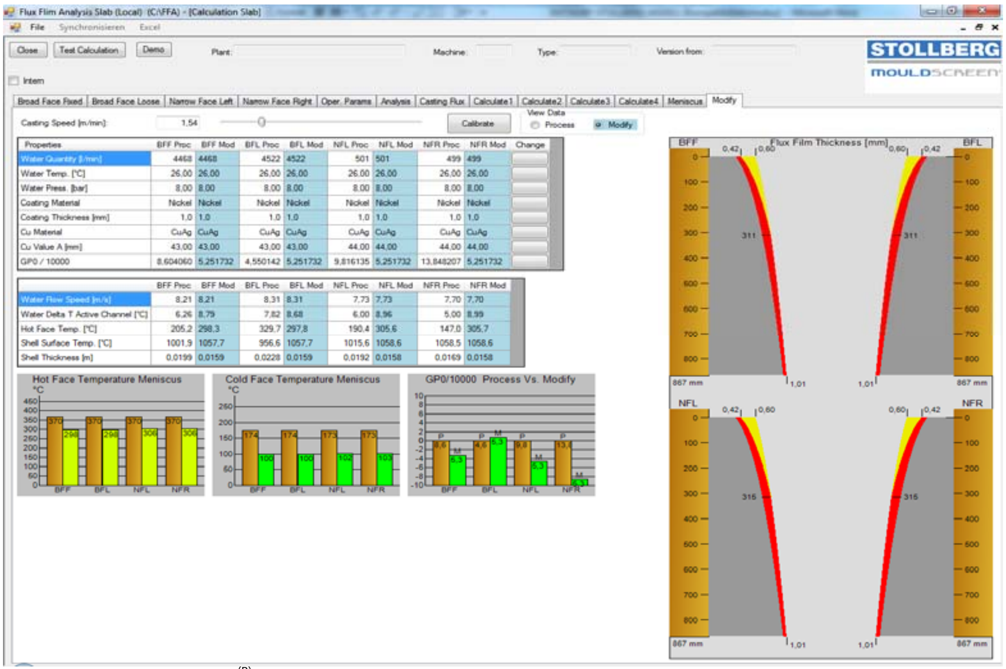
Figure 5. Data output screen: strand shell thickness, slab surface temperature, local and integral heat flux density across active mould length.

Another window contains the information of copper plate skin temperature and flux film thickness. The left section of Figure 6 provides the average value of the copper plate temperatures together with the averaged thermocouple measurements, if available. The hot-face temperatures are shown in red, cold face temperatures in blue, and the measured temperatures readings are shown as green circles. The program's forecast for the thermocouples is shown as a dotted line. Again, the already known data windows allow a comparison of copper plate temperatures for the broad and narrow faces across the active mould length. The slab surface temperature and the copper plate skin temperature of the hot face define the thermal environment for the casting slag. Hereby, the characteristic slag temperatures and the solid and liquid fraction of the flux film can be determined. The right section of Figure 6 shows the total flux film thickness in grey, the thickness of the solidified layer in blue, the thickness of mushy layer in red, and the liquid slag is shown in yellow. The influence of different assumptions about the thermal conductivity of the slag is expressed by the solid respectively dotted lines (not visible in Figure 6). The graph shows, that the important liquid flux film (lubrication) does not always reach to the mould end.

Figure 6. Data output screen: copper plate temperatures, thermo-couple readings and film thicknesses and flux conditions.

Calculations of layer thickness of the liquid and solid fraction in flux film for a large variety of slab and thin slab moulds were already published.(3-7) As expected, considerable differences in the behaviour of the casting slag at different casting speeds were detected. In order to further investigate the influence of different operation scenarios and design features of continuous casting moulds on flux film thickness and condition, the "Modify"- tool was developed. It is a novelty in the assessment of powder performance in continuous casting. The tool can analyse different operating scenarios for a given mould and display the results by mouse click. The main "Modify" (Figure 7). It is subdivided into different data windows and graphics.
The left section of the screen shows a compilation of information about the currently running continuous casting process. The bar charts indicate the temperature conditions in the meniscus area. The right section shows for the two mould broad faces (top) and narrow faces (bottom) the solid, mushy and liquid fraction of the flux film. "Modify" can either display the current condition state ("process"), or a variant ("modify") calculated by the tool. By using a radio button, the modified and the current condition state can be switched back and forth. Now a direct assessment of the casting process with a variation of casting powder or for the modification of the

operating parameters is possible by the push of a button. The question: "What happens if for example casting speed, cooling water supply pressure or temperature changes?" will be answered by the MouldScreen® Modify tool online.



Casting Speed [m/min]: 1,54

View Data: ○ Process ● Modify

Properties	BFF Proc	BFF Mod	BFL Proc	BFL Mod	NFL Proc	NFL Mod	NFR Proc	NFR Mod	Change
Water Quantity [l/min]	4468	4468	4522	4522	501	501	499	499	
Water Temp. [°C]	26,00	26,00	26,00	26,00	26,00	26,00	26,00	26,00	
Water Press. [bar]	8,00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	
Coating Material	Nickel	Nickel	Nickel	Nickel	Nickel	Nickel	Nickel	Nickel	
Coating Thickness [mm]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
Cu Material	CuAg	CuAg	CuAg	CuAg	CuAg	CuAg	CuAg	CuAg	
Cu Value A [mm]	43,00	43,00	43,00	43,00	44.00	44.00	44,00	44,00	
GP0 / 10000	8,604060	5,251732	4,550142	5,251732	9,816135	5,251732	13,848207	5,251732	

	BFF Proc	BFF Mod	BFL Proc	BFL Mod	NFL Proc	NFL Mod	NFR Proc	NFR Mod
Water Flow Speed [m/s]	8.21	8.21	8.31	8.31	7,73	7,73	7,70	7,70
Water Delta T Active Channel [°C]	6,26	8,79	7,82	8,68	6.00	8,96	5,00	8,99
Hot Face Temp. [°C]	205,2	298,3	329,7	297,8	190,4	305,6	147,0	305,7
Shell Surface Temp. [°C]	1001,9	1057,7	956,6	1057,7	1015,6	1058,6	1058,5	1058,6
Shell Thickness [m]	0,0199	0,0159	0,0228	0,0159	0,0192	0,0158	0,0169	0,0158

Figure 7. The MouldScreen® Modify Tool: displays the variation of different operational parameters and their impact on copper plate temperatures as well as solid, mushy and liquid fraction of the flux film.

Here, of course, combinations of changes in the operating parameters are possible. At this point, the benefits of analytical modelling and the resulting mathematical formulation of physical relationships are evident. For the offline mode, also variations of copper plate material and thickness as well coating material and thickness are provided.

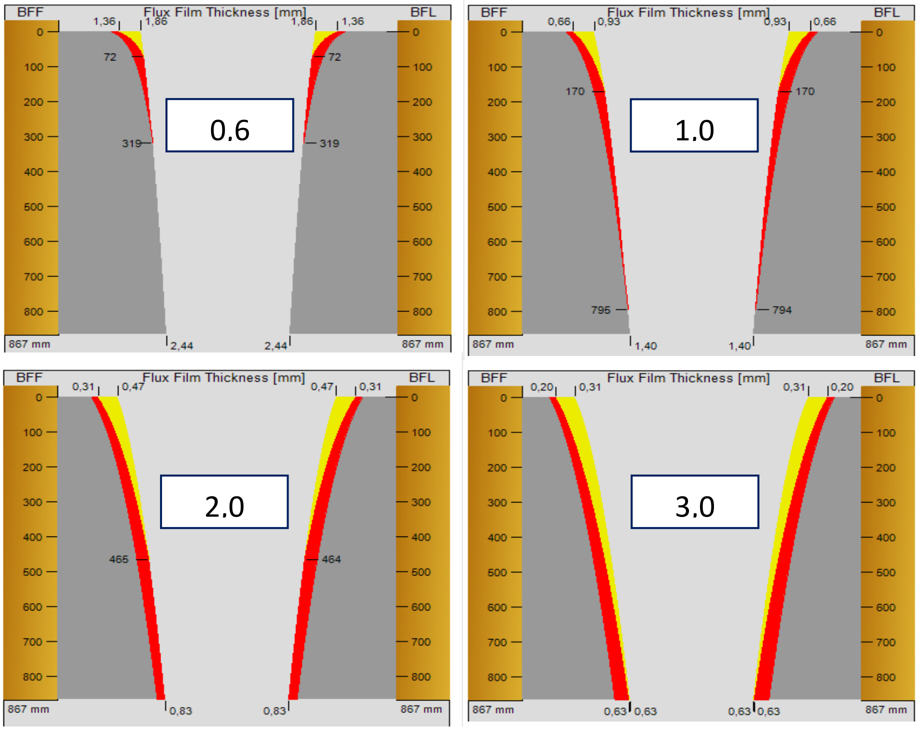


Figure 8. The variation of casting speed (0.6, 1.0, 2.0, and 3.0) m/min with MouldScreen® Modify tool and the resulting changes of the flux film.

Figure 8 shows as an example, the influence of casting speed on the liquid and solid fraction of the flux film. The survey includes only screen shots of the broad faces. The casting speed can be varied by a sliding bar and the results will appear immediately on the screen. The behaviour of the four mould plates is visualized separately. The example in Figure 8 uses four different speeds (0.6 m/min, 1.0 m/min, 2.0 m/min and 3.0 m/min) and compares them with each other. The pictures were taken from an operating state with v_c = 1.15 m/min by using the "Modify-v_c” controller. As shown in Figure 8, the proportions of liquid, mushy and solid flux film change across the active mould length in the four sub-images. With higher casting speeds the liquid fraction reaches deeper into the mould. Simultaneously the film gets thinner. In the example shown, the predicted values at meniscus for the broad face (fixed side) decrease from 1.86 mm (at 0.6 m/min) via 0.93 mm (at 1.0 m/min) to 0.47 mm (at 2.0 m/min) to finally 0.31 mm (at 3.0 m/min). The latter number is close to the production speed range of slow-casting thin slab machines.

4 FIRST RESULTS MEASURED BY PROTOTYPE INSTALLATION AT A SLAB CCM IN GERMANY

In December 2011 the MouldScreen® software was installed at a German slab producer in order to compare the calculation and visualization results of the MouldScreen® system with the standard recordings. This counts in particular for data recorded during unstable casting conditions such as sticker alarms. In the following, a sticker event detected by the standard sticker detection system is visualized by the MouldScreen® system and evaluated.

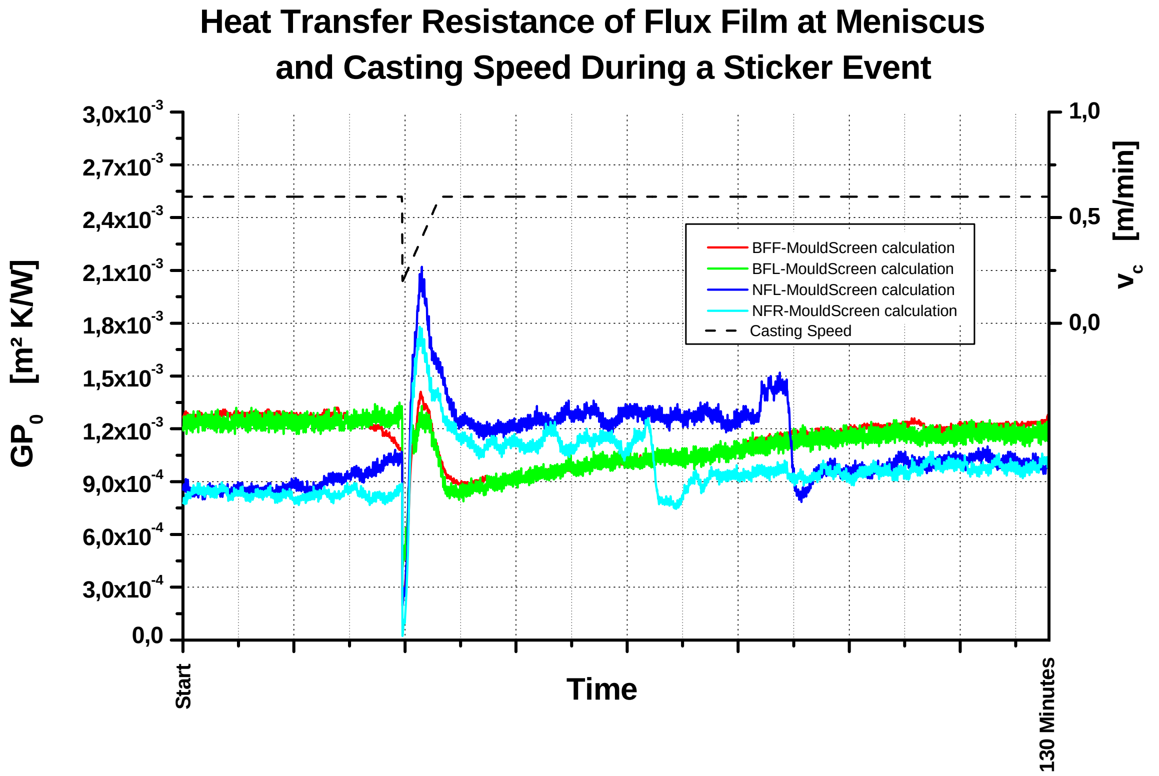


Figure 9. Calculated values of the heat transfer resistance of flux film at meniscus and related casting speed before, during, and after a sticker event.

Figure 9 shows the heat transfer resistance of the flux film in the area of the meniscus (GP$_0$). Indicated is a casting period of approximately 130 minutes. The following results of the MouldScreen® algorithm for broad- and narrow faces are displayed (see legend). At the beginning (start) the values of GP$_0$ for the broad faces amount to 0.0012 m^{2}K/W and for the narrow face to 0.0009 m^{2}K/W. That means, the flux film in this case is thicker on the broad faces compared to narrow faces. It is assumed, that the flux film has the same thermal conductivity around the entire meniscus area. The observation period shows a sticker event, detected by the sticker detection system and compensated with a drop in casting speed. At the time of the event and even prior to that, a significant disturbance of the flux film thickness is noted. After initial high amplitudes this distortion calms down gradually. Remarkably, after the event the values of flux film thickness of the narrow faces are thicker vs. broad faces. Towards the end of the observed time period the GP$_0$ values slowly return to initial levels, whereas the broad face values are constantly rising after the event the narrow face values accomplish that by two clearly notable jumps.

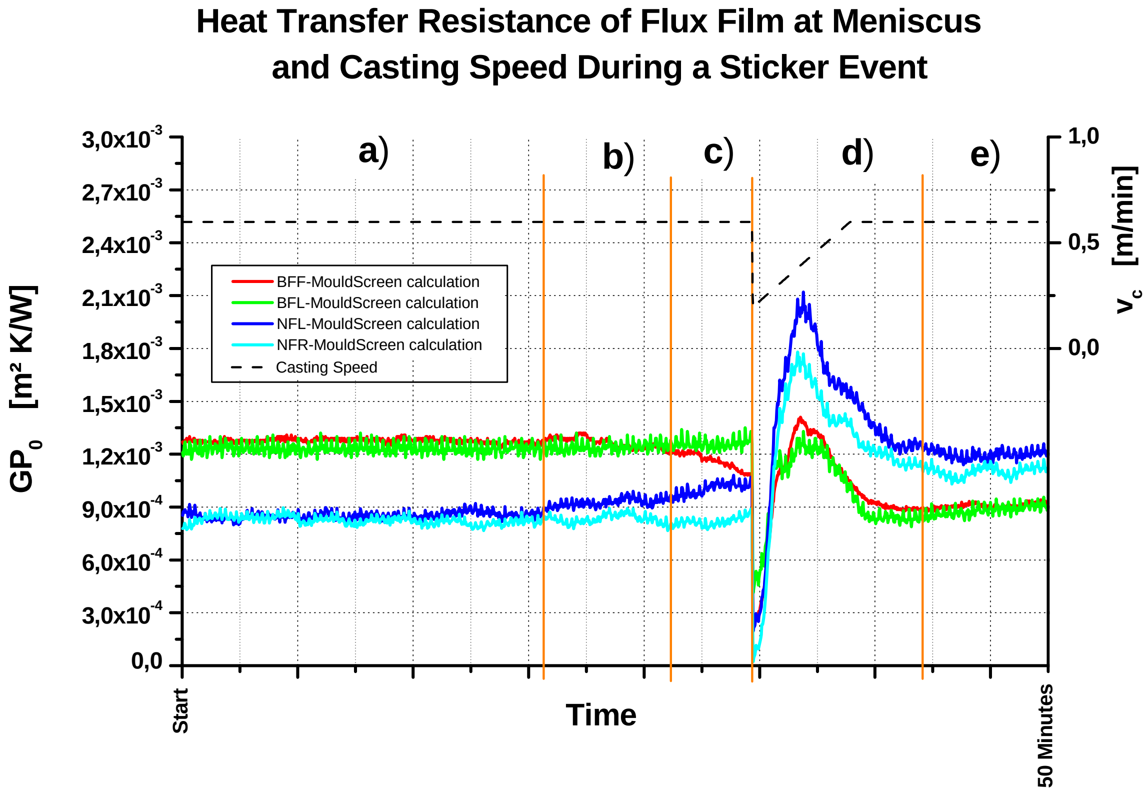


Figure 10. Characteristic time segments (a - e) before and after the sticker alarm.

The different casting phases (prior and after the sticker event) denoted in Figure 10 mean in detail:

- Phase a) normal casting conditions. Both broad faces have the same constant flux layer film thickness, this also applies to the narrow sides. However, the layer thicknesses of the narrow faces are less compared to wide faces.
- Phase b) the broad face fixed (BFF) and narrow face left (NFL) values of GP_0 are unstable, they are moving towards each other. At the end of phase b) the GP_0 value of NFL has already moved away from NFR.
- Phase c) The GP_0 value of BFF decreases to such an extent that it matches the value of NFL just before triggering the sticker alarm. This suggests that the cause of the alarm (sticker) lies in the area between NFL and BFF.
- Phase d) At the beginning of this phase the sticker alarm was triggered by the thermocouples of the sticker detection system and the casting speed was reduced. Subsequently the machine slowly resumed casting speed back to initial value. It can be recognized that all GP_0 values (all 4 copper plates) undergo massive disturbances; starting with a sudden drop followed by rebound. The two narrow faces even reach higher GP_0 values than the broad faces (GP_0 inversion).
- Phase e) After resuming to casting speed set-point the process stabilizes; however, initially keeping the GP_0 inversion. As noted in Figure 9 already the GP_0 values return much later to their initial levels

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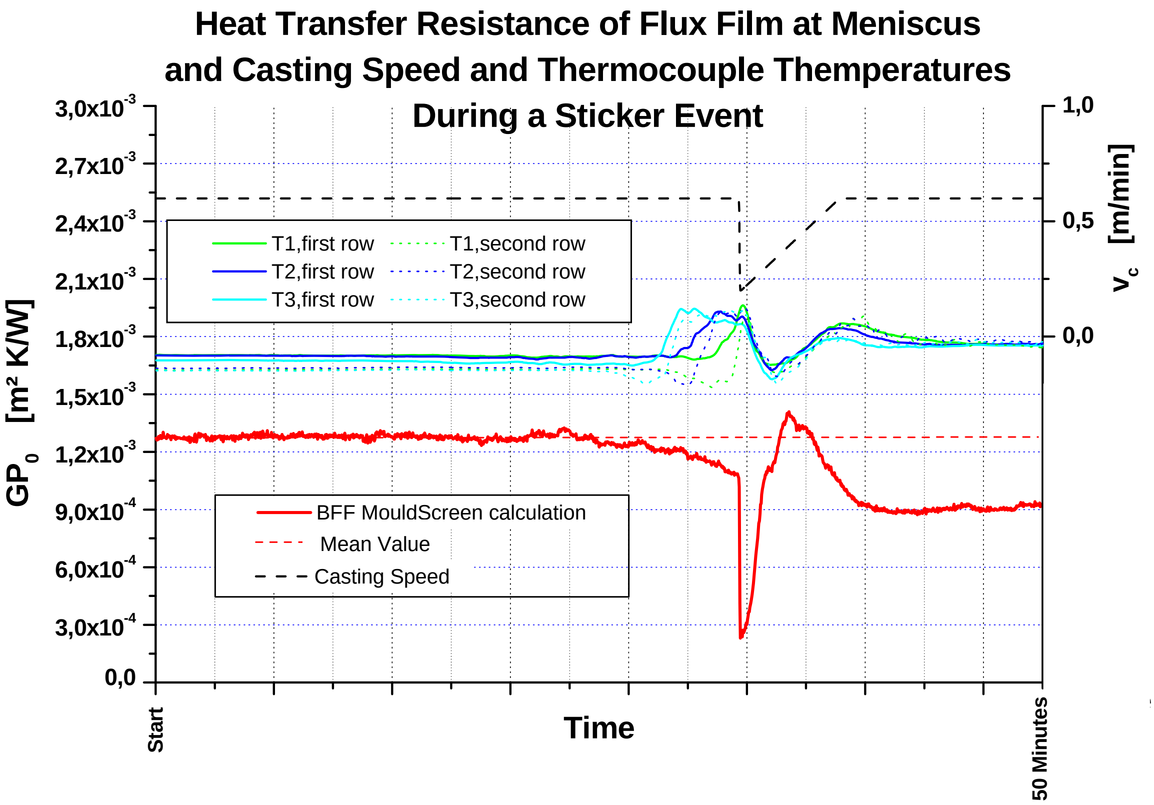

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read

Figure 11 shows the same period as Figure 10, but only the GP_0 for BFF is indicated. The thermocouple measurements, which have triggered the alarm, are shown in the middle of the diagram (without scale in order to be graphically clear). There are two thermocouple rows (first row, second row), showing the characteristic pattern of a sticker alarm. It can be clearly seen that the depicted GP_0 curve deviates from the "mean-value" significantly even before the sticker alarm. The "mean value" of GP_0. BFF is indicated by the red dashed line and was estimated from the mean of the data in the undisturbed state. After the sticker alarm the trial was continued for a while with inverted GP_0 values of broad- and narrow faces, until first NFR and then NFL returned to their normal level. Meanwhile, the GP_0 values of the BFF and BFL slowly but steadily recovered to normal levels (Figure 9, right side).

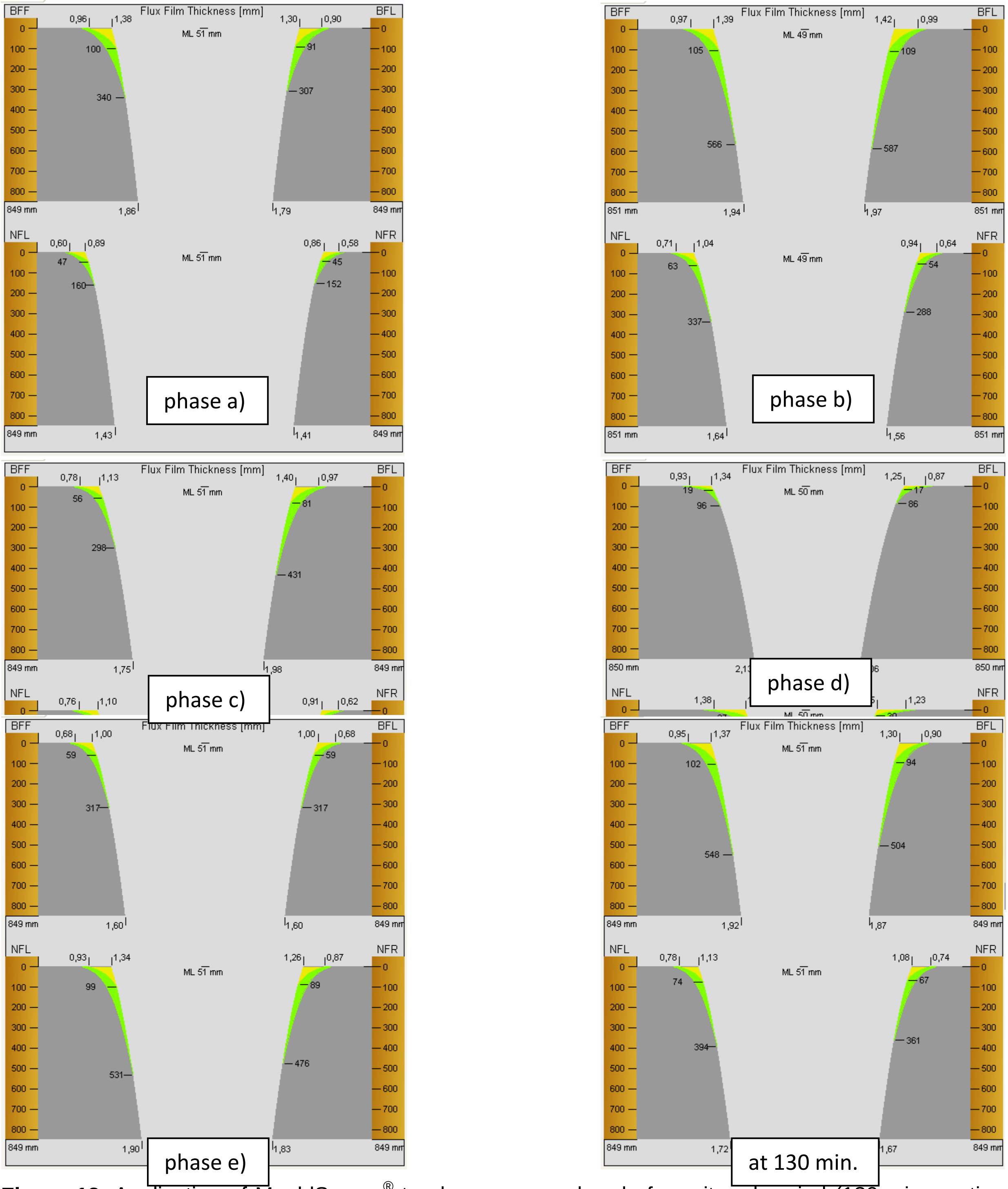

Figure 12. Application of MouldScreen® to phases a-e and end of monitored period (130 min. casting time).

Figure 12 shows a sequence of screen shots prepared with the MouldScreen® modify tool for the phases a) to e) and a screen shot of a time point late in the example considered here (Figure 9, at about 130 minutes). In contrast to Figures 9 to 11, in the modify tool directly displays the flux film thickness for all four copper plates (BFF, BFL, NFL, NFR). This requires knowledge of the thermal conductivity of the flux film. In the upper part of the mould, the total thickness is subdivided into the liquid (yellow) and the mushy (green) fraction. For ease of reference the various thicknesses and depths of the layers are in mm. The location of the corresponding isotherms is given by the chemical composition of the mould powder. The mould level and the active mould length are also shown.

The picture for phase (a) (Figure 12, top left) shows that the broad faces have a thicker flux film than the narrow faces and that the liquid and mushy fractions on the broad faces reach deeper into the mould.

During phase (b) (Figure 12, top right) all flux films grow thicker and the penetration of liquid and mushy fraction increases. This suggests that changes in the flux film are taking place, leading to the sticker eventually.

Just before the alarm sticker the flux film thickness and penetration depth of BFF, BFL and NFR regresses. The NFL however, forms a flux film almost identical to BFF. See phase (c) (Figure 12, middle left). The thermocouple recordings (not shown here) reveal that sticker alarm was triggered by a rise in temperatures in the edge region between BFF and NFL. The course of the curves of GP_0 BFF and NFL just before the alarm (Figure 10), shows already the approach of the two values towards each other.

Figure 12 middle right shows the situation in flux film in phase (d) when shortly after the alarm the casting speed is resumed slowly. The flux films of all copper plates except for BFL are significantly thicker than in phase (c). On the narrow faces flux film thicknesses of about 2.5 mm are reached at end of mould. The liquid and mushy fractions regress during the ramping-down phase and phase (d) already displays that their depths are inverted (swopped). That means that the narrow faces have now deeper mushy and liquid fractions as well as larger layer thicknesses compared to broad faces.

This effect continues through the stabilization of the process in phase (e) (Figure 12, bottom left). As already visible in Figure 10 the higher GP_0 values of the narrow faces (GP_0 inversion) are again visible. The layer thicknesses and depths behave similarly in phase b), but with reversed roles of the narrow- and broad faces.

As shown in Figure 9, it seems that in this example the flux film did not reach a final stable state beyond phase (e). As already mentioned, the broad and narrow faces return only after a long time back to its normal state. While the broad faces accomplish this gradually, the narrow faces do this abruptly. Figure 12 bottom right shows a data set of the new steady state at about 130 minutes casting time. As previously displayed in phase (a) the broad faces show now layer thicknesses and penetration depths greater than the narrow faces. Also the liquid and mushy fractions are now more pronounced than in the (unstable) initial phase.

5 CONCLUSION

In order to assess the influence of different steel grades, mould powders and design features and operating methods of continuous casting moulds (e.g. copper material, copper plate thickness, casting speed, and water flow) on the behaviour of the flux film, the MouldScreen® software has been developed. It is now possible to monitor and visualize new parameters to increase production safety and to optimize quality. For a given mould, “Modify” analyses various operating scenarios and presents the results by mouse click. Immediate assessment of the casting process in case of variation of powder/slag properties, casting speed, water quantity or even mould design is possible. The MouldScreen® “Modify Tool” is a novelty in monitoring the continuous casting process.

The first trial runs at a slab CCM in Germany reveal that by applying MouldScreen® valuable new signals are created. The interpretation of these new signals might lead to quality and process improvements and help eliminating false alarms of sticker detection systems.

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