The Influence of Mould Powder Properties on Shell Formation in Continuous Casting of Steels

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For peritectic steel grades the shell formation is uneven resulting in quality problems such as surface cracks. Production of these steels calls for good control and knowledge of the critical factors for shell formation. By optimisation of process parameters, it is possible to enable production of crack sensitive slabs for heavy plate. This also gives a unique possibility to study the interaction between process parameters and shell formation. The paper presents the results from two large investigations with this ambition covering the total of 27 + 30 heats of 220 tons of steel at SSAB EMEA-Oxelösund and concludes how surface cracks can be significantly decreased.

Keywords: Steelmaking, continuous casting, shell formation, mould powder

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Introduction

The formation of a steel shell in the mould during continuous casting is a complicated process influenced by a large number of variables, such as the following parameters (as illustrated in **Figure 1**):

- Steel temperature
- Melt flow (SEN design)
- Mould design (taper etc.)
- Mould properties (thermal conductivity, plating's etc.)
- Oscillation parameters (frequency, stroke length, non sinusoidal mould movement)
- Mould slag lubrication (viscosity, solidification temp)
- Thermal properties of mould slag (thermal conductivity, absorption)
- Crystallisation behaviour of mould slag

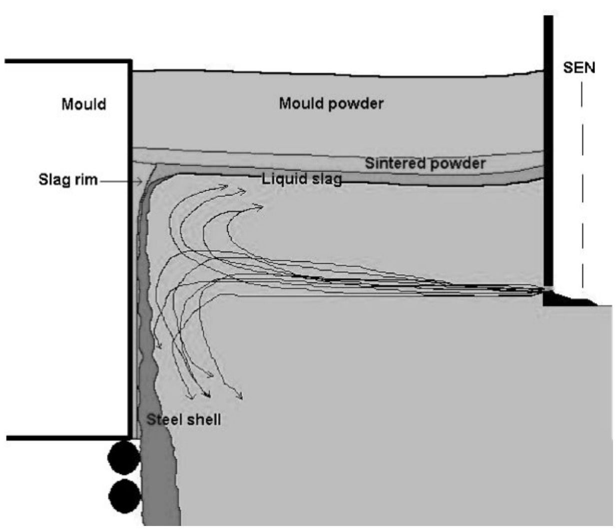

Figure 1. Schematic figure of a slab mould (half section).

For a lot of years the research team for Casting & Solidification of Swerea KIMAB has performed a number of research projects, based on plant trials, in co-operation with Swedish steel companies. These studies have provided information about the interaction of some of the above mentioned variables regarding shell formation. From this work we want to highlight two large investigations made at SSAB EMEA-Oxelösund:

- Influence of mould-powder, geometry and oscillation on heat transfer and slab quality for a micro-alloyed peritectic steel [1].
- Minimization of longitudinal cracks for a Nb-Ti-B steel during slab casting at SSAB EMEA, Oxelösund [2-3].

Influence of Mould-powder, Geometry and Oscillation on Heat Transfer and Slab Quality for a Micro-alloyed Peritectic Steel

For the project one common steel grade was chosen which is designed for the production of heavy plate products and is ideal for that purpose. As often is the case, an ideal composition for the end product is not ideal when it comes to the casting. The slab casting of this and similar steel grades (peritectic, micro alloyed steels) is difficult for the following reasons:

- The carbon content is 0.13 wt.%, which gives a large peritectic transformation at a narrow temperature interval.
- The ferrite potential is 0.91 according to the definition stated by Manfred Wolf [4]. As a result, the steel shell will solidify in an irregular way due to shrinkage in connection with δ-ferrite/γ transformation combined with a strenghtening of the shell by a factor of 2 to 3 due to the transformation to austenite which has a larger high-temperature strength.
- The micro alloying elements, V, Al and N result in precipitations of VN and AlN. This gives a surface of low

ductility, at a critical temperature region, due to a large grain size combined with an accumulation of precipitates in the grain boundaries [5].

The slabs of these steel grades are prone to transversal wide face– and corner cracks and the choice of parameters for both in-mould as well as secondary cooling are crucial in the ambition to produce slabs with a low defect rate.

Experimental procedure. All experiments were made at SSAB EMEA-Oxelösund on CC machine No. 2 with data given in **Table 1**. For the chosen steel grade a typical steel composition is shown in **Table 2**.

The following process parameters were chosen to be studied:

- Mould powder properties with respect to heat transfer.
- Mould geometry with respect to design and taper of the narrow face.
- Oscillation parameters with respect to negative strip time.

Mould powders. Three different mould powders were chosen with the ambition of keeping most properties unchanged except for crystallinity, which was varied primarily by choosing three mould powders with different basicity (Bas), A: Bas = 1.19, B: Bas = 1.06 and C: Bas = 0.88. The difference in crystallisation behaviour was revealed by the break temperatures, evaluated from viscosity measurements to be 1267, 1242 and 1165 °C respectively.

Mould geometries. A proper support of the narrow face is crucial in avoiding transversal wide face and corner cracks. If the support is unsufficient a depression normally takes place on the wide face 50–100 mm from the corner. When this area looses contact with the mould it will become reheated and the grain growth of the secondary structure will be enhanced. In designing an ideal shape of the narrow face the shrinkage of the corners must also be considered. Two-dimensional solidification studies at KIMAB revealed that the corner shrinkage is much greater than could be expected and a total corner shrinkage of up to 4° was verified. To countervail this effect, a mould was constructed where the upper part of the narrow sides is concave which compensate for the corner shrinkage. The chosen variables were thus (i) a straight mould with normal taper, (ii) a concave mould (5 mm-top, 0 mm-bottom) with normal taper at the corners and (iii) a concave mould (5 mm-top, 0 mm-bottom) with 1 mm larger taper than normal at the corners.

Table 1. Data for slab machine No. 2 at SSAB EMEA Oxelösund.

Metallurgical length, m	Slab thickness, mm	Slab width, mm	Soft reduction
28	220, 290	900–1680	Yes

Table 2. Example of chemical composition from the studied steel grade, wt-%.

C	Si	Mn	V	Ti	Al	N	P	S
0.13	0.44	1.38	0.035	0.010	0.027	0.009	0.008	0.009

Oscillation parameters. For transversal wide face and corner cracks the oscillation marks act as crack initiation points, and minimising the oscillation mark depth reduces the risk for crack formation. It is also well known that reducing the negative strip time will reduce the oscillation mark depth [6]. A too short negative strip time will result in insufficient feeding of mould powder in the gap between strand and mould why this matter calls for optimisation. In this study the negative strip time was varied in three steps: Long (0.18–0.21 s), medium (0.14 s) and short (0.10 s).

Based on these three variables a statistical research matrix was made which resulted in 27 trials divided in three campaigns which were performed at three different occasions. All tests were made with sequence casting and three heats per sequence.

Process parameters. All heats were cast with the following process parameters:

- Slab dimensions: 1680 mm • 220 mm
- Mould height: 785 mm
- Casting speed: 1.2 m/min
- Heat weight: 220 metric tons
- Set point temperature in tundish: 1535 °C (liquidus 1514 °C).
- Cup SEN.

The process trials were carefully followed up and the ordinary process data collecting system was complemented by the installation of two vertical rows of thermocouples close to the east corner on the upper side of the strand at different distances below meniscus. The thermocouples on the wide face were mounted at a distance of 85 mm from the corner and the thermocouples on the narrow face at a distance of 15 mm from the corner. All thermocouples were mounted at a distance of 10 mm from the copper-shell interface.

Mould powder characteristics. The most important data regarding the mould powders which were used during the trials are shown in **Table 3**. The viscosity and break temperature were measured with the Bähr Vis 403 rotometer viscosimeter at SSAB-EMEA Oxelösund. As can be seen from Table 3 the viscosity is almost the same for all three mould powders but the break temperature differs a lot.

Table 3. Data from mould powders used in the investigation.

Mould powder	A	B	C
Heat flux	low	medium	high
Basicity, CaO/SiO_2	1.19	1.06	0.88
Viscosity at 1300 °C, Poise	2.72	3.06	2.51
Break temperature, °C	1267	1242	1165

Results: Heat flux in the mould. The heat flux in the mould is calculated based on the temperature difference between inlet and outlet cooling water and the flowrate. To evaluate the mean heat flux only stable periods were chosen. The first period of 20 minutes, which is influenced by starting powder, is excluded as well as a 20-minute period after the powder grade was changed. Also periods with reduced casting speed were excluded. An example of the evaluation of the mean values of all four sides from campaign No. 2 is shown in **Figure 2**.

The influence of process parameters on the mould heat flux was evaluated with a multiple regression analysis using Design-Expert^{TM} software with the following results:

- A reduced linear model could be found with good significance (R-squared 0.73).
- Narrow face mould geometry showed no significance and was excluded from the model.
- The basicity had a very strong impact on the heat flux, which also has been shown in a previous investigation at SSAB EMEA-Oxelösund [7].
- The model equation was found to be: q [kW/m^2] = 2206 – 814 · Basicity – 158 · Negative strip time.

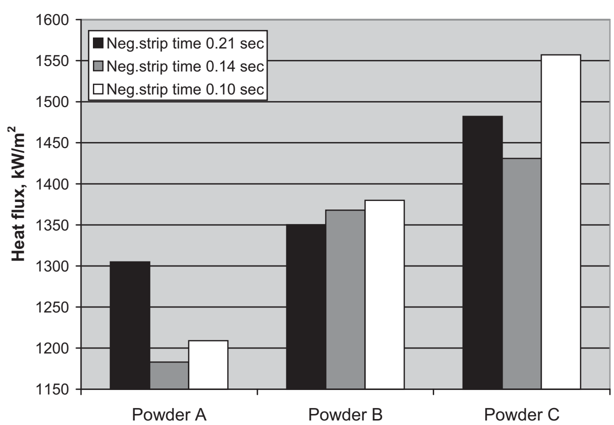

Figure 2. Mean heat flux in mould for test campaign No. 2.

The strong influence of mould powder basicity is a consequence of a higher ability of crystallisation. This leads to a reduction of heat flux by a thicker solid slag layer in the mould and also by blockage of the influence of radiation. It was also noticed that the size of the rim in the meniscus is larger for the high basicity fluxes.

A minor influence from a negative strip time is obvious, which can be explained by the correlation between negative strip time and depth of oscillation marks. A large negative strip time results in deeper oscillation marks which are filled with slag and/or gas, which will decrease the heat flux in the mould.

Results from temperature measurements. The data from the temperature measurements were collected once per second. An example for the wide face of campaign No. 2 is shown in **Figure 3**. The mould powder A, which gives the lowest heat flux in the mould, also shows the lowest temperature from thermocouple measurements.

Results on oscillation mark depth. From each heat a slab sample of 500 mm length was collected, as illustrated in **Figure 4a**. These were used for both metallographic investigations and studies of the oscillation mark depth on the narrow face. Using a laser based topographic measurement technique, an evaluation of the local oscillation mark depth could be done. In order to determine how the different factors influenced the OSM-depth, a multiple regression analysis was made which gave the following model: OSM-depth (mm) = 0.49 + 1.11 · Neg.strip time – 0.30 · Basicity. A reduced linear model gave the best fit (R-squared = 0.63) and the correlation according to the model is shown in **Figure 4b**.

Evaluation of slab surface quality. All 27 heats within the investigation were very carefully evaluated regarding cracks as CL = longitudinal cracks and CN = other crack types. A multiple regression analysis was made which is presented in **Table 4**. To make the evaluation possible a summation was made of the narrow face mould taper and

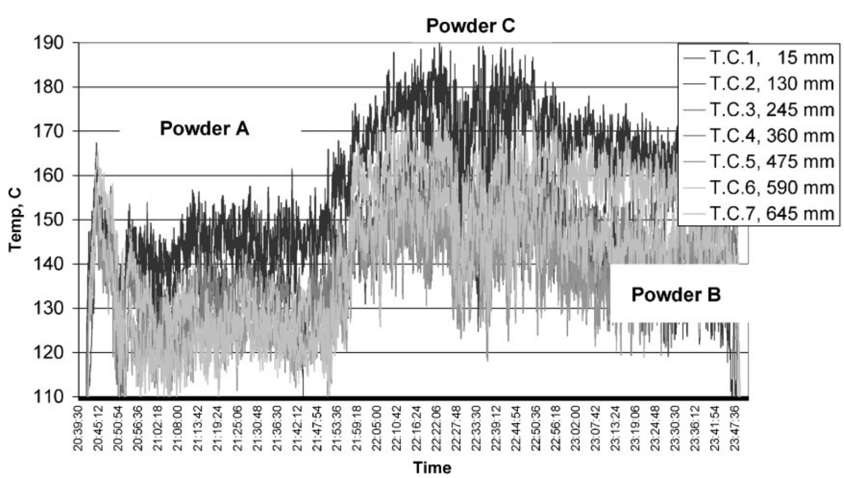

Figure 3. Thermocouple measurements from campaign No. 2, wide face, sequence No. 2, trial No. 13–15.

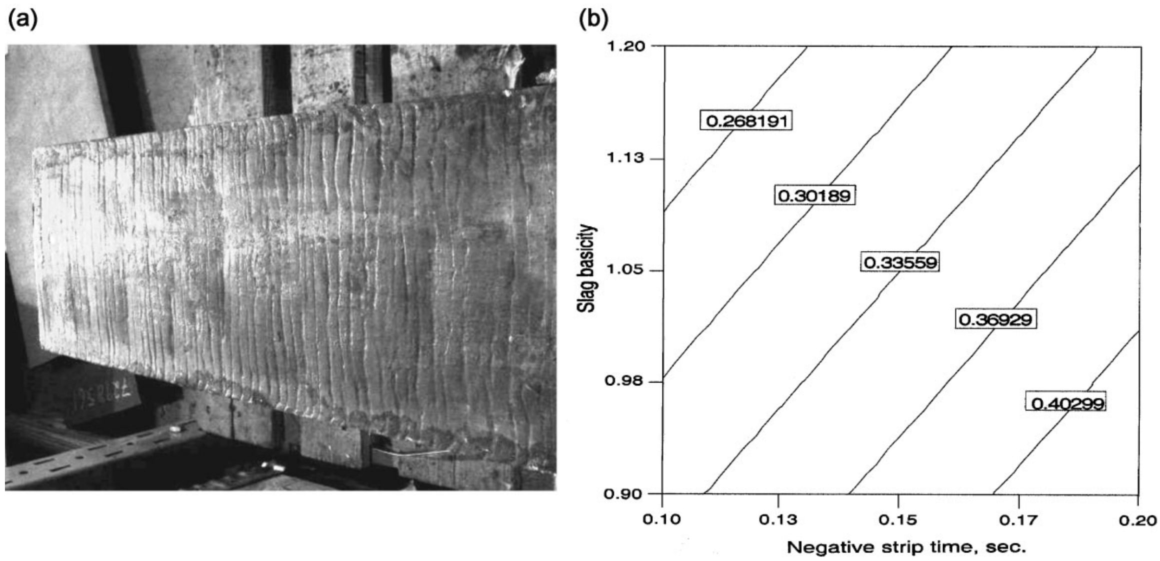

Figure 4. OSM-measurements, a) Picture from the narrow face, b) OSM-depth as function of negative strip time and basicity.

Table 4. Statistical models for surface cracks.

Type of cracks	Significant variables	Type of responce surface model	Significans of model, R-squared	Model
Longitudinal	N^2, C, B	Reduced quadratic	0.53	$CL = 0.08 + 3.43 \cdot N–0.005 \cdot C–0.07 \cdot B-1.19 \cdot N^2$
Transversal	N, C, B	Linear	0.87	$CN = 26.8 + 12.4 \cdot N-1.6 \cdot C-5.2 \cdot B$
Open corner	N, C	Reduced linear	0.27	$CN = 0.81-1.79 \cdot N-0.03 \cdot C$
Hidden corner	N	Reduced linear	0.37	$CN = 10.4 - 50.1 \cdot N$

concavity, which means taper in the middle of the narrow face. The variables are thus defined as: N = negative strip time, B = basicity, C = concavity + taper (8.2, 14.2 and 13 mm). The output responses: CL = crack length (m/m), CN = number of cracks/m.

Longitudinal midface cracks. The bottom of the oscillation marks often act as starting points for longitudinal cracks. For that reason a high basicity mould powder apart from promoting "soft cooling" is also good because it reduces the depth of the oscillation marks. A short or long negative strip time is positive. A long time causes increased inflow of mould powder slag resulting in even cooling of the strand, a short time leads to reduced oscillation mark depth.

Transversal cracks. The transversal cracks normally emerge at a distance of approx. 50–100 mm from the corner on the loose side. The concave mould has a very strong positive influence on reducing the cracks due to the better contact which is established between the mould and strand in this area. A high basicity mould powder is positive because of "soft cooling" which results in a short meniscus and reduced risk for the creation of "hooks". Another positive effect of high basicity is reduced oscillation mark depth, which is also favoured by a short negative strip time.

Open transverse corner cracks. These cracks appear at all four corners. A long negative strip time is positive because of better lubrication and more even cooling in the corner area. The concave mould is also beneficial because of better contact.

Hidden transverse corner cracks. The cracks appear mostly at the corners of the fixed side. The only found significant variable was that a long negative strip time is positive. A possible explanation is that this results in enhanced lubrication and by that a hotter surface of the corner. This in turn keeps the temperature above the critical ductility level when the strand passes the bending part, 2–3.5 meter below meniscus, where the cracks can emerge.

Results from metallographic investigations. From each heat one slab sample of about 500 mm length was taken for detailed studies regarding oscillation mark depth and metallographic examinations. The slab samples were sectioned so that the surface could be studied 15 mm from the corner on the narrow face and 85 mm from the corner on the loose wide face, that is the same positions where the thermocouples were situated. Samples of approx. 300 mm length were prepared for metallographic examinations and etched with Nital. **Figure 5** is an example from a sample with

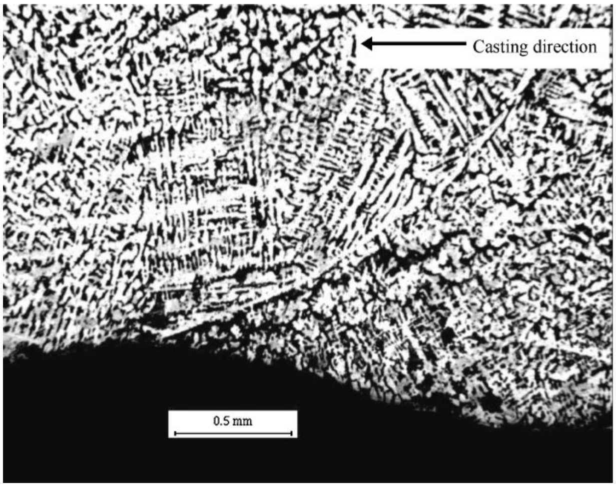

Figure 5. Surface cast structure with a hook, trial No. 12, wide face. Magnification 50x.

a marked so-called “hook”. The surfaces were studied and deviations from normal appearance, such as cracks, pinholes and “hooks” were notified. The results from campaign No.1 and 2 are presented in **Figures 6 to 9** from which the following conclusions can be drawn:

- “Hooks” are rare on the wide face and not found with the low conductive mould powder A. This is a consequence of mild cooling in this area.
- On campaign No. 1 with the straight mould, cracks were found on the narrow face with all mould powders.
- In trial No. 2, with the concave mould, these cracks vanished and instead, the number of observations with “hooks” increased, which is a consequence of a better contact between mould and strand at the narrow face.

Conclusions. From the multiple regression analysis it became clear that there is no ideal set of process parameters that will result in a minimum of all surface defects. The ideal parameters have to be chosen in order to achieve the best results which give the least quality problems on the end

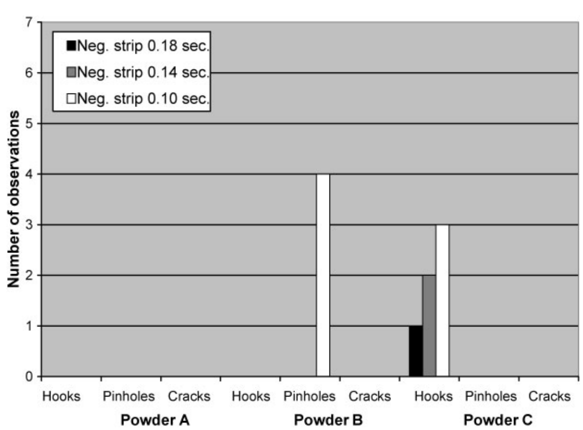

Figure 6. Observations of slab surface deficiencies from campaign No. 1, wide face, straight narrow face.

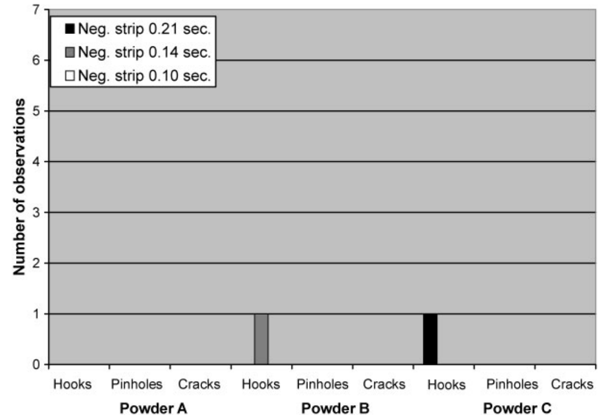

Figure 7. Observations of slab surface deficiencies from campaign No. 2, wide face, concave narrow face.

product. At SSAB EMEA-Oxelösund the transversal and hidden corner cracks are experienced to result in most quality problems in the production of slabs for heavy plate production. This is also illustrated in **Figure 10** which shows the average surface defects from the whole investigation.

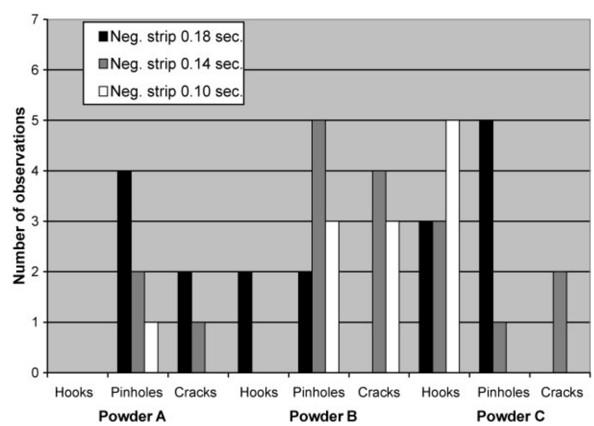

Figure 8. Observations of slab surface deficiencies from campaign No.1, straight narrow face.

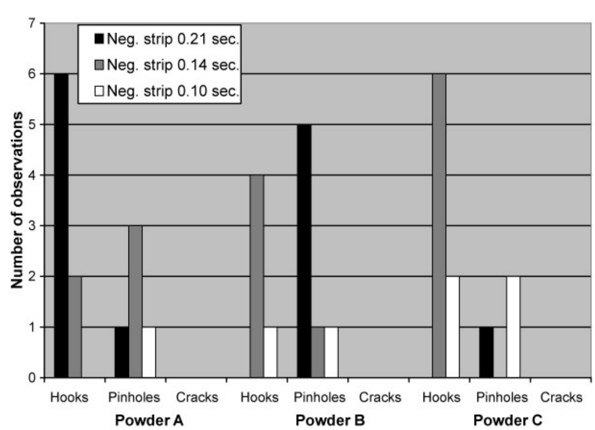

Figure 9. Observations of slab surface deficiencies from campaign No. 2, concave narrow face.

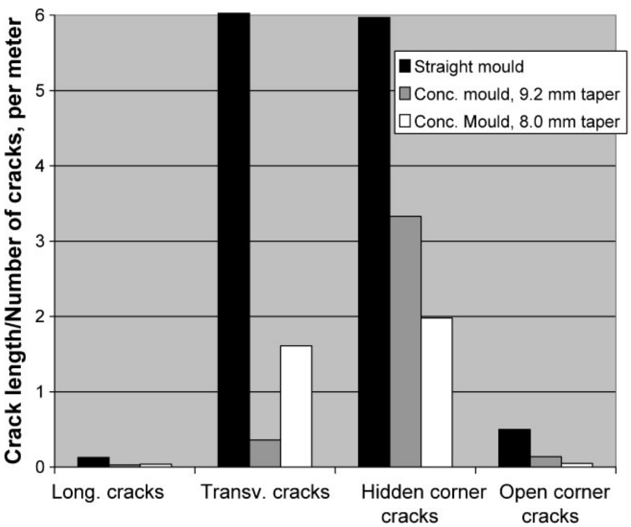

Figure 10. Mean value of surface defects.

According to the statistical analysis the ideal process parameters can be summarized as follows:

- Low heat conductive mould powder achieved by a high basicity ($CaO/SiO_2 = 1.20$).
- Mould with concave narrow faces compensating for corner shrinkage.
- Appropriate narrow face taper (9.2 mm at the corner in this case).
- Medium negative strip time (0.14 seconds).

Minimization of Longitudinal Cracks for a Nb-Ti-B Steel during Slab Casting at SSAB EMEA-Oxelösund

Micro-alloyed peritectic steel grades with low nitrogen levels, alloyed with titanium, are not sensitive for transversal cracking due to lack of formation of aluminium nitrides. The main problem with production of these steels at SSAB EMEA in Oxelösund is instead longitudinal cracking which mainly occurs on the loose side of the strand, preferably in the middle of the slab at the SEN position. The cracks are supposed to arise in hot spots at the slab surface owing to lower solidification rate and/or due to mechanical tensions caused by the upper bending zone propagating upwards to the mould while the CC machines in Oxelösund are constructed with a straight mould and an upper bending zone.

In order to find optimum process casting parameters, with the goal to reduce the amount of longitudinal cracks, a statistically planned study was made including 30 heats from 9 sequences' with the following process variables:

- Narrow face taper (3 levels).
- Steel flow, SEN design (2 levels).
- Mould slag viscosity (3 levels).
- Mould oscillation, amplitude (3 levels).
- Mould oscillation, frequency (3 levels).

In addition to these planned variations a natural variable occurred, the superheat of the melt. From the trials, where the slabs were very carefully inspected, a multi-variant statistical analysis was conducted with the following output parameters:

- Cooling effect at the narrow face plates (kW/m^2).
- Cooling effect at wide face plates (kW/m^2).
- Amount of longitudinal cracks (crack length per meter slab).

Experimental procedure. All experiments were carried out at SSAB EMEA-Oxelösund on CC machine No. 1 with the data given in Table 1. For the chosen steel grade a typical steel composition is shown in **Table 5**.

The basic process parameters for all studied heats were:

- Slab format: 220 mm•1680 mm
- Casting speed: 1.2 m/min
- Secondary cooling: Same for all heats.
- Concave narrow face mould plates.

The variables for the study are shown in **Table 6**.

Because of different bottom design the Cone SEN had an estimated higher speed of around 30% up along the narrow sides compared to the Cup SEN. The design of mould powder composition was aimed to reach the desired variations in mould powder viscosity without influencing the crystallisation properties (break temperature), which were around 1270 °C.

The process trials were statistically planned and analysed according to the analysis of variance (ANOVA), furthermore the data were evaluated with the aid of the software Design-Expert® [8]. The analysis of the cooling effect gives a background knowledge which helps to understand the effect on crack formation.

Results - cooling effect of narrow face moulds. A reduced 2FI model gave a predicted R-squared of 0.83 which is a good correlation. Oscillation frequency (B) and a number of interactions were removed because of low statistical significance. The perturbation analysis is shown

Table 5. Example of chemical composition from the studied steel grade wt-%.

C	Si	Mn	Ti	Al	Nb	B	C_{ekv}
0.12	0.5	1.4	0.022	0.035	0.018	0.002	0.104

Table 6. Casting parameters for the study.

Casting parameter	Variables		
	low	medium	high
Narrow face taper, mm	7.7	8.4	9.1
SEN bottom design (flow speed)	Cup		Cone
Measured mould slag viscosity, Poise	1.70	2.10	2.65
Mould oscillation amplitude, mm	2.5	3.4	4.4
Mould oscillation frequency, mm	95	103	110

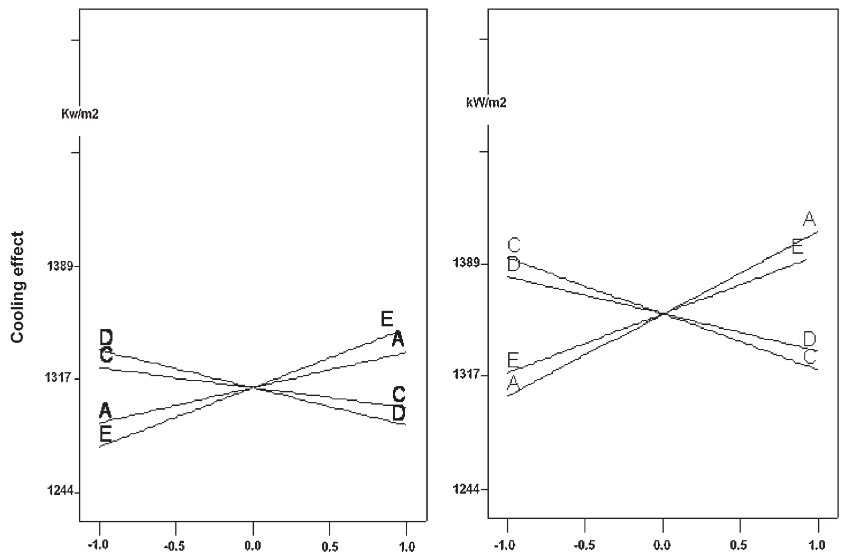

Figure 11. Perturbation analysis of mould effect of narrow face, kW/m^2, a) Cone SEN design, b) Cup SEN design.

in **Figure 11** where A = osc. amplitude, C = narrow face taper, D = mould slag viscosity, E = superheat.

The following explanation is given to Figure 11:

- *Mould oscillation amplitude (A):* Strong increase with increased amplitude for both SEN designs. This seems to be an effect of increased feeding of mould slag creating better heat transfer between mould and shell, which means that the feeding of slag is done during the negative strip time, see **Figure 13** because a change in amplitude causes a strong change in negative strip time but has little influence on the positive strip time (**Figure 14**).
- *Narrow face taper (C):* Reduced cooling effect with increased taper due to better contact and by that formation of more even and thicker shell.
- *Mould slag viscosity (D):* Reduced cooling effect with increased slag viscosity probably due to a thicker slag thickness between mould and shell and/or formation of gas-gaps which gives higher insulation.
- *Superheat (E):* As expected a higher heat flux for a higher superheat of the melt. Same for both SENs.
- *Comparison of heat flux in mould:* The total heat flux is much higher for the Cup SEN compared to the Cone SEN (1357 kW/m^2 versus 1310 kW/m^2) which at a first thought is a bit confusing while a high impact of fluid flow ought to give a higher heat flux in the mould. The explanation is probably that the Cone SEN creates a standing wave which prevents a good downfeed of mould slag at narrow sides.

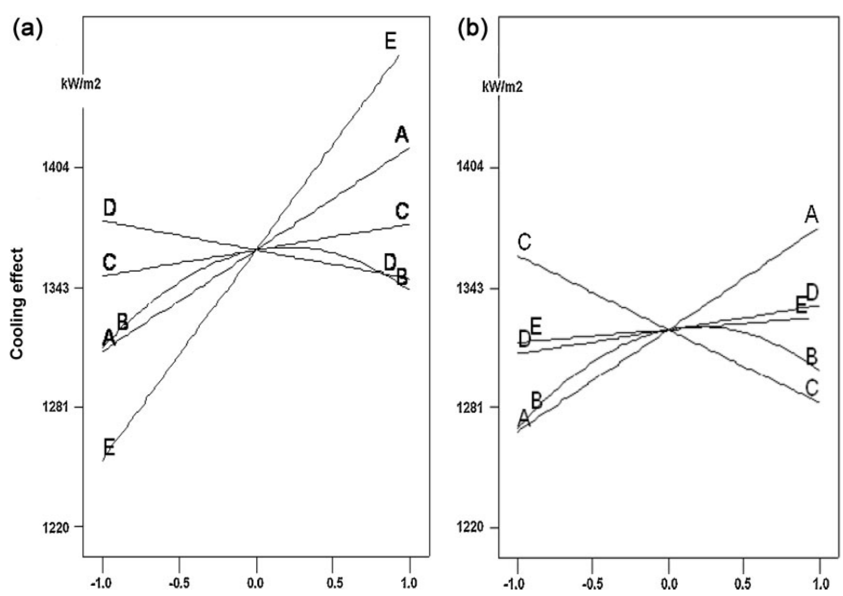

Figure 12. Perturbation analysis of cooling effect at wide face, kW/m^2, a) Cone SEN, b) Cup SEN.

Results - cooling effect of wide face moulds. A reduced quadratic model gave a predicted R-sqared of 0.90, which is a good correlation. All variables showed a good statistical relevance except mould slag viscosity which anyway could be used in the model because of statistically relevant interactions. The perturbation analysis is shown in **Figure 12**.

The following explanation is given to Figure 12:

- *Mould oscillation amplitude (A):* Strong increase with increased amplitude for both SEN designs. This seems to be an effect of increased feeding of mould slag creating better heat transfer between mould and shell, which means that the feeding of slag is done during the negative strip period (Figure 13 and 14).
- *Mould oscillation frequency (B):* No large influence at either SEN due to comparatively small influence on negative strip (Figure 13).
- *Narrow face taper (C):* Cone SEN: No large influence due to weaker narrow side shell; Cup SEN: Strong decrease with increased taper. Formation of a strong narrow face shell, due to good feeding of slag, could lead to inward bending of the shell removing the wide face shell from the mould.
- *Mould slag viscosity (D):* Small influence with both SEN.
- *Superheat (E):* Cone SEN: Very large increase with increased superheat which is to be expected due to higher melt flow rates at wide sides including also meniscus area; Cup SEN: Small increase due to lower melt flow rates compared to Cone SEN.
- *Comparison of heat flux in mould:* The total heat flux is higher for the Cone compared to the Cup SEN design (1360 kW/m^2 versus 1321 kW/m^2) because of the above mentioned explanation.

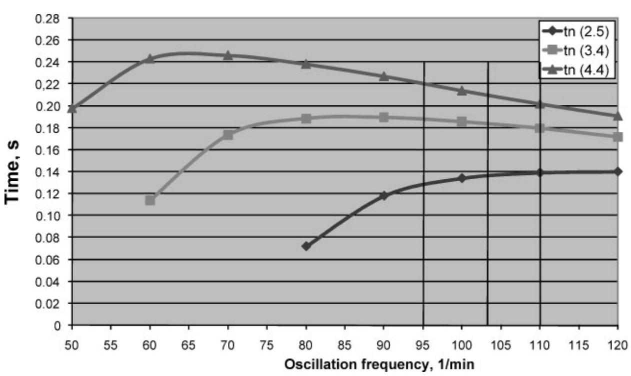

Figure 13. Negative strip time as function of oscillation amplitude and frequency.

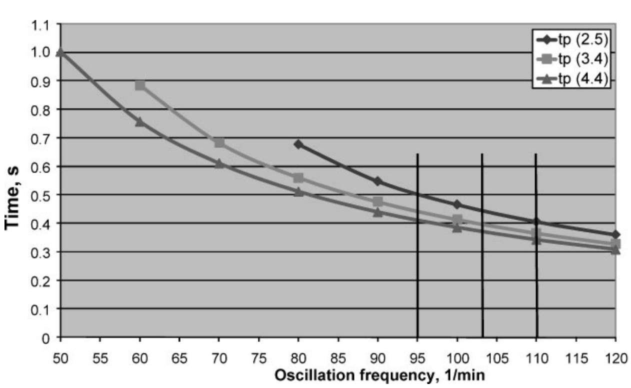

Figure 14. Positive strip time as function of oscillation amplitude and frequency.

Optimisation regarding minimization of longitudinal cracking. The analysis with DesignExpert gives an opportunity to study the effect of different variables in 3D using a so- called desirability index (DI). This means that DI should be 1 to fully avoid longitudinal cracks in slabs. For this study a calculation of DI was performed for both the Cone and Cup SEN design. The optimum parameters excluding viscosity and superheat are shown in **Table 7**. The 3D presentations encompass the parameters which are most difficult to control, that is slag viscosity, which can change due to temperature and chemical interaction with the steel, and superheat. In **Figure 15** the results from the calculations are shown with mould slag viscosity on the X-axis and superheat on the Y-axis. A steep border at 15 °C superheat is deliberately introduced because this is out of the process window due to the risk of freezing at the end of casting. The figure clearly shows the process window where the flat surface with DI = 1 shows the area which is 100% free from longitudinal cracking.

Conclusions

There are two ways to avoid longitudinal midface cracks:
Cone SEN:

- At low superheat (< 20 °C) it is possible to avoid cracks for all mould slag viscosities.
- The strong fluid flow from the Cone SEN causes shell thinning at higher superheat.
- For casting at higher superheat it is preferred to use a high viscosity mould powder.

Cup SEN:

- At high superheat (> 22 °C) it is possible to avoid cracks for all mould slag viscosities.
- High superheat does not cause shell thinning because of the low flow rate from the Cup SEN but it results in a warmer meniscus close to the SEN where the longitudinal cracks emerge.
- Higher superheat promotes casting powder melting which is strongly restricted in this area because of low flow rate of the liquid steel.

Table 7. Process parameters for minimisation of longitudinal cracking

SEN design	Cup	Cone
Osc. amplitude, mm	3.4	3.4
Osc. frequency, 1/min	104	104
Narrow face taper, mm	9.1	8.1

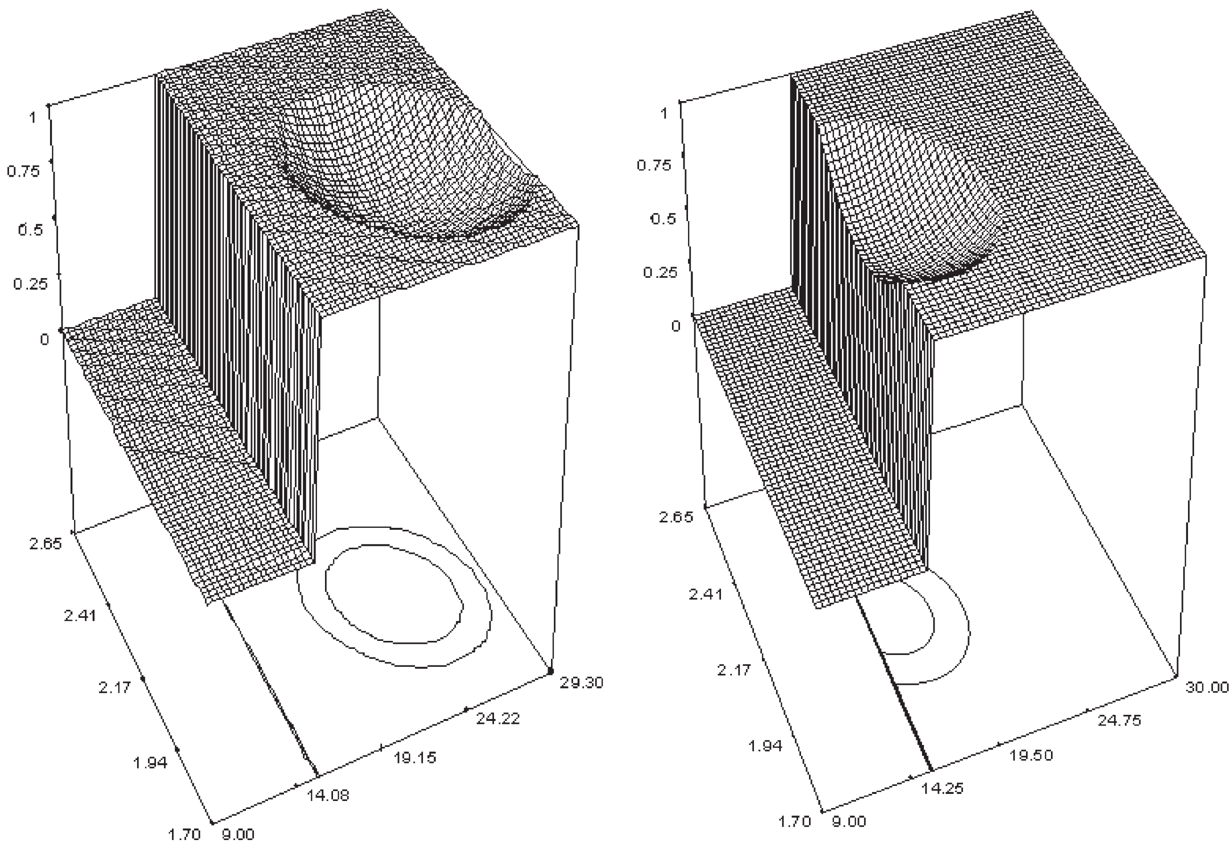

Figure 15. Desirability index for a) Cone SEN b) Cup SEN. X-axis = superheat, Y-axis = slag viscosity.

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