

## 3D THICKNESS MEASUREMENT TECHNIQUE FOR CONTINUOUS CASTING BREAKOUT SHELLS

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### Abstract

The shell thicknesses following a breakout have been accurately measured using a laser scanner and the variations in shell thickness were related to mould thermal monitoring data.

The highly detailed 3D thickness scans confirm that local variations in shell thickness may occur in the mould. In combination with mould thermal monitoring, the root cause of these thickness variations was identified.

In this paper, the breakout shells from two incidents at the high speed thin slab caster at the Direct Sheet Plant (DSP) are discussed. The first breakout is related to entrapment of a large inclusion on the wide face. The second is a narrow face breakout related to localised shell thinning and incorrect taper settings.

In both cases, the breakouts were associated with local reductions in shell thickness. Mould thermal temperatures at these locations identified a reduction in thermocouple temperatures, indicative of an 'air' gap or insulating layer between the steel shell and copper. Additional calculations using CON1D were used to verify the existence of an insulating layer and to give a better understanding of the events that led to these breakouts.

### Introduction

With the help of the laser thickness measurement technique, an adaptation of a thickness measurement laser technique, normally used to measure and evaluate automotive body parts, the shell thickness of two breakouts from the Direct Sheet Plant at Tata Steel Mainland Europe in IJmuiden was measured accurately.

The two breakouts shells studied with this technique were breakout A, due to an inclusion entrapment in the west-wide face; and breakout B, a taper breakout in the south-narrow face.

During the results evaluation, it was noticeable that in both breakouts, the shell has no constant thickness and displays three kinds of thinning:

- local thinning in the longitudinal direction
- local thinning in the vertical direction
- thinning in areas of the shell

Some of the thinnings appear together with longitudinal and transverse cracks.

The measurement of the shell thickness was also compared with the thermocouple signals, where thinner shell show low temperature, and thicker shell show higher temperature values.

### 3D laser measurement techniques

For measuring the breakout shells a 3D Digitizer (ATOS) in combination with an optical coordinate measuring machine (TRITOP) were used [1].

ATOS is a flexible optical measuring machine based on the principle of triangulation (*Figure 1*) projected fringe patterns are observed with two cameras. 3D coordinates for each camera pixel are calculated with high precision, a polygon mesh of the object's surface is generated [1].

*The principle of triangulation:* The distance between the laser source and sensor is known. The laser shoots light at the object being measured and this is reflected back to the sensor via the lens. Point b can be calculated from knowing a, c and distance D.

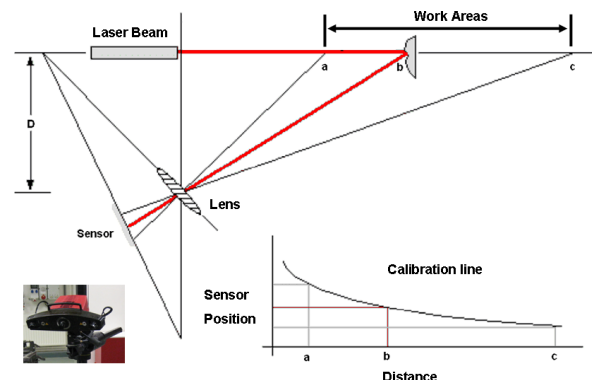
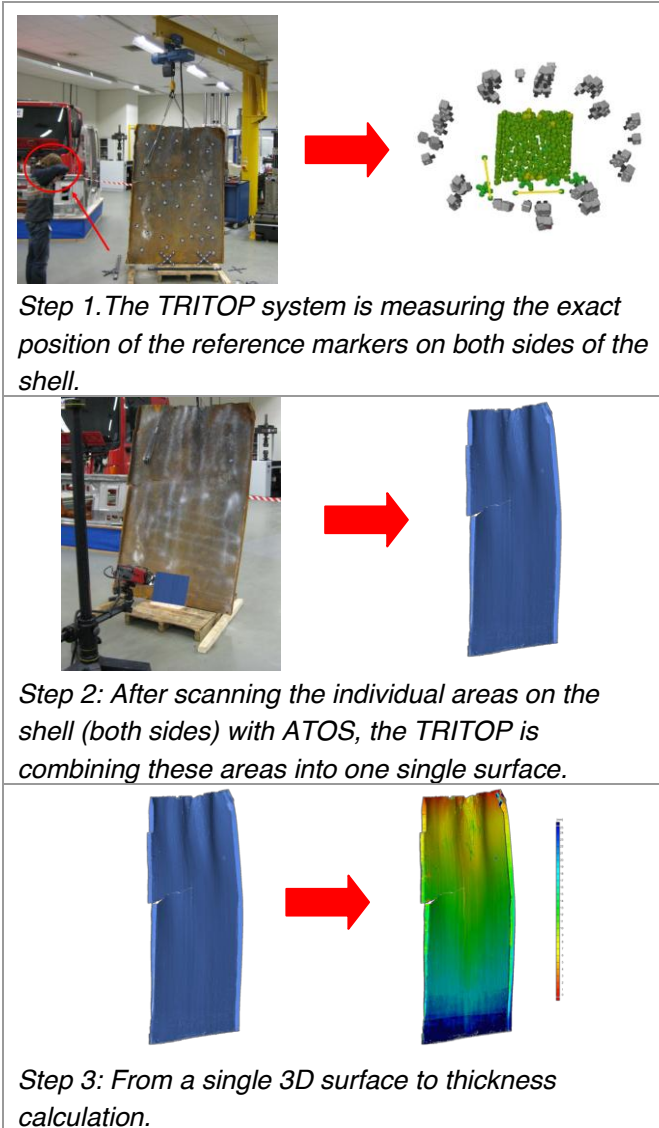


Figure 1. The principle of triangulation

TRITOP is an optical coordinate measuring machine. This mobile technology is designed to define the exact 3D position of markers (telemetry). TRITOP is used to identify the reference markers on both sides of the shell to support the ATOS measurements. When both sides of the shell are in the same coordinate system, a 3D thickness calculation is possible [1]. *Figure 2* shows a short illustration of the measuring procedure in three steps.



*Figure 2. The measuring procedure in three steps*

## Examples of breakout analysis

### Breakout A

While casting in the Direct Sheet Plant thin slab caster, a low range-HSLA steel (high strength low alloyed), during a ladle change, a breakout occurred. Before the breakout, the thermocouples temperatures and the other process parameters were very normal and with almost no signs of instability. Then a few minutes before the breakout, the casting speed was reduced due to mould level fluctuations.

Considering that the cause of the breakout was unknown, it was decided to study the shell with this new technique.

Therefore, the shell was put aside for further analysis and its thickness was measured with the 3D laser technique.

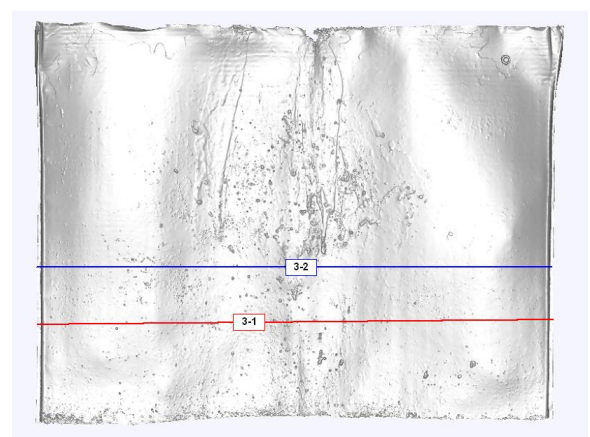


*Figure 3. Breakout shell (loose side)*

*Figure 3* shows a photo of the breakout shell used for further analysis.

### 3D Laser measurement

Due to the breakout hole and some splashes attached to this breakout side of the shell, the opposite side of the breakout was used in the laser measurement. Therefore, the full fixed face side and half of both narrow sides were used for the measurement. *Figure 4* shows the half-breakout shell under study.



*Figure 4. The half-breakout shell under study. Lines blue and red are used for the thickness-plane measurements.*

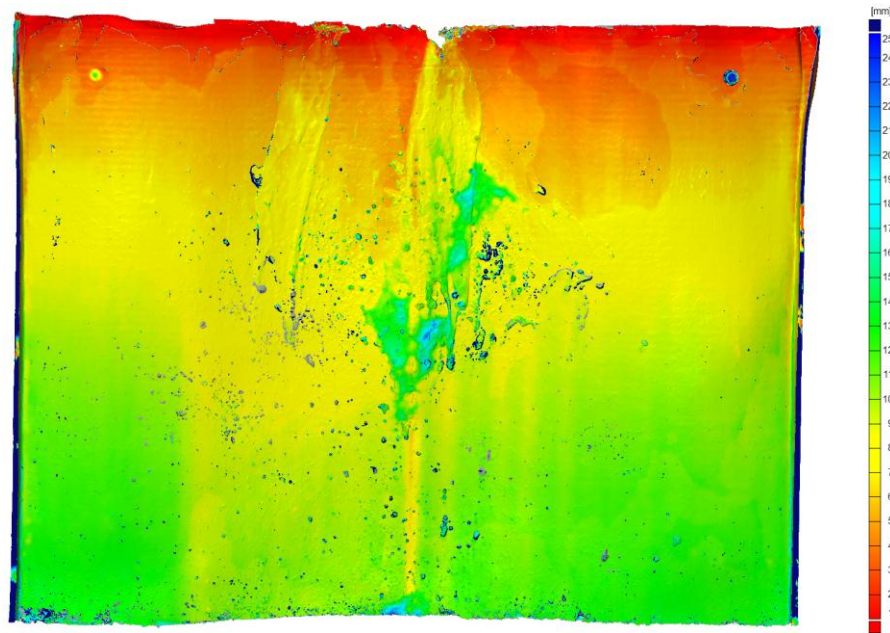


Figure 5. A 3D view of the shell thickness.

A 3D view of the shell thickness is shown in *Figure 5*. In this image it is noticeable that the breakout shell has no constant thickness and displays three kinds of thinning:

- local thinning in the longitudinal direction
- local thinning in the vertical direction
- thinning in areas of the shell

The localised reduction in the thickness is about 50%, compared with other areas; especially in the longitudinal direction.

#### Thickness measurement

To be able to clarify the reduction in thickness, two positions were used to measure the shell thickness along a line (lines in red and blue in *Figure 4*).

Results of these positions compared with the 3D view are shown in *Figure 6*.

The lines show more clearly the reductions in thickness of the shell, indicating the localised and areal thinnings.

#### Breakout B

During a slag rim removal, a breakout occurred while casting a HSLA steel (high strength low alloyed) in the Direct Sheet Plant. . Before the breakout, the thermocouples temperatures were very unstable and the cause of the breakout was unknown. For that reason, it was also decided to study the shell with the 3D laser technique.

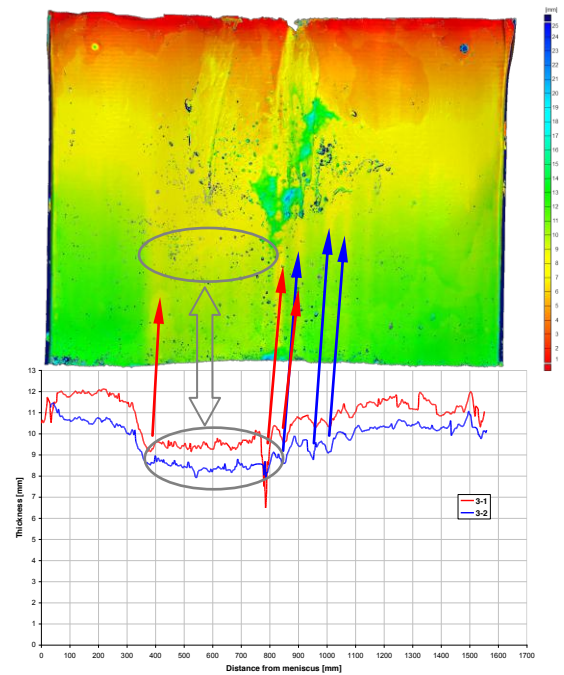


Figure 6. Results of the line measurements compared with the 3D view.

Consequently, after the breakout event, the breakout shell was put aside for further analysis, and the breakout shell was studied and its thickness measured with the 3D laser technique. *Figure 7* shows a photo of the breakout shell.





Figure 7. Breakout shell.

### 3D Laser measurement

Considering that the breakout shell was in a good condition, the laser measurement was done in two parts:

Part 1: half of the loose side and half of each narrow face

Part 2: full fixed side and half of each narrow face, including half of the breakout hole.

Part 1 will be shown as a reference.

Part 1: The full east wide face (fixed side) and half of both narrow sides were used for the measurement.

Figure 8 shows the half-breakout shell under study. In the middle of this half-shell a longitudinal crack was found (circled in white). In red the distances of the crack to meniscus and from the south narrow face are shown.

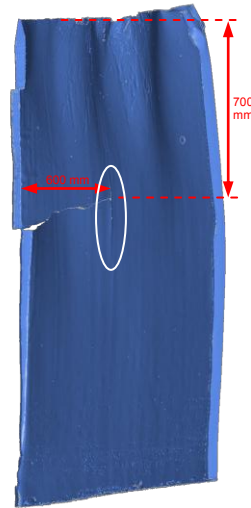


Figure 8. Half-breakout shell under study. Into the white oval the LFC is shown.

A 3D view of the shell thickness is shown in Figure 9.

In this image it is noticeable that the breakout shell has no constant thickness and again displays the same three kinds of thinning as in breakout A:

- local thinning in the longitudinal direction
- local thinning in the vertical direction
- thinning in areas of the shell

The localised reduction in thickness is also about 50% , compared with other areas; especially in the longitudinal direction (longitudinal crack).

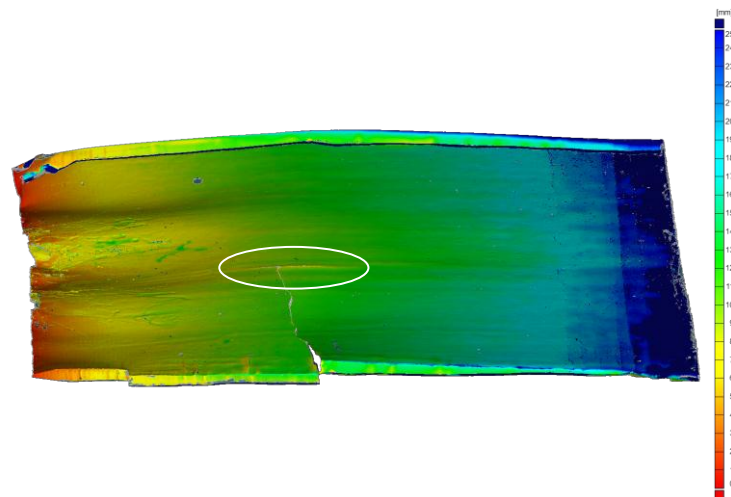


Figure 9. A 3D view of the shell thickness.

In figures Figure 9 and Figure 10, the longitudinal crack is marked with a white oval. The transverse crack in this breakout occurred during the extraction of the breakout shell from the machine because the extraction of the shell was done from the top of the mould; however it obviously had a transverse local thinning of the shell in the corner region to initiate this cracks (thinning marked in Figure 11, blue line).

### Thickness measurement

To be able to clarify the reduction in thickness, several positions were used to measure the shell thickness along a line.

Two sets of positions were chosen in part of the breakout, three in the transverse direction and three in the longitudinal direction. In Figure 10 a schematic view of the line's positions is shown.

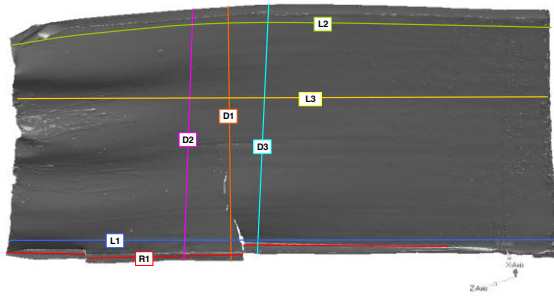


Figure 10. Schematic representation of the sections for thickness measurement.

The lines were chosen as follows:

- R1 (red line): longitudinal plane in the narrow face (south), about 15 mm from the corner.
- L1 (blue line) and L2 (green line): also longitudinal sections, approximately at 15 mm from the corner, L1 close to the south narrow face and L2 close to north narrow face.
- L3 (dark yellow line): Longitudinal section to compare the thickness of the shell between the middle and the sides of the slab.
- D1 (orange line): in the middle of the longitudinal crack
- D2 (pink line) and D3 (turquoise line): both at end and beginning of the crack, respectively.

Results of these positions compared with the 3D view are shown in *Figure 11* for the longitudinal sections and in *Figure 12* for the transverse sections.

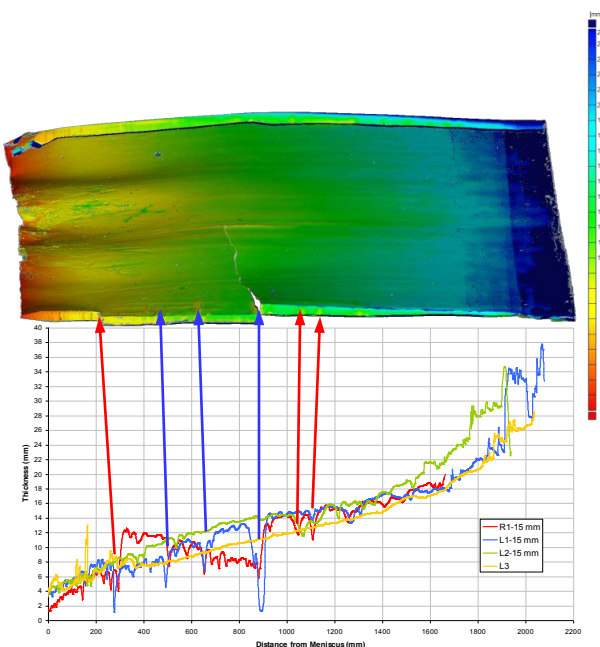


Figure 11. Results of the longitudinal sections compared with the 3D view

Again the lines show more clearly the reductions in thickness of the shell, indicating the localised and area reductions.

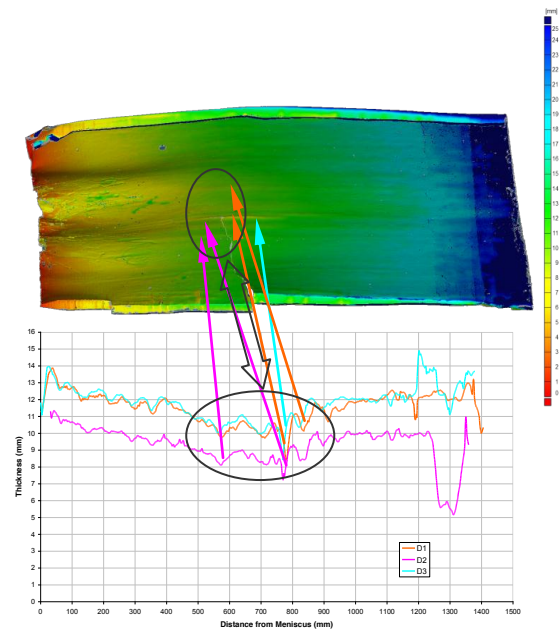


Figure 12. Results of the transverse sections compared with the 3D view.

#### Surface profile

The 3D laser measurement has also the possibility to evaluate the surface profile (smoothness) of the breakout shell (*Figure 13*).

Considering the localised reductions in thickness of the shell, it is interesting to see the inside and outside surface profiles of the breakout shell.

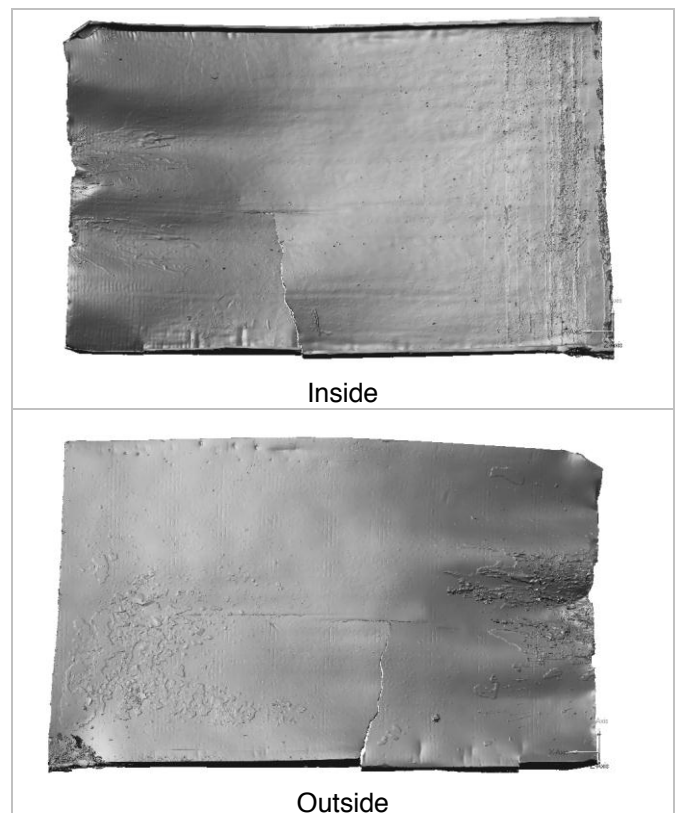
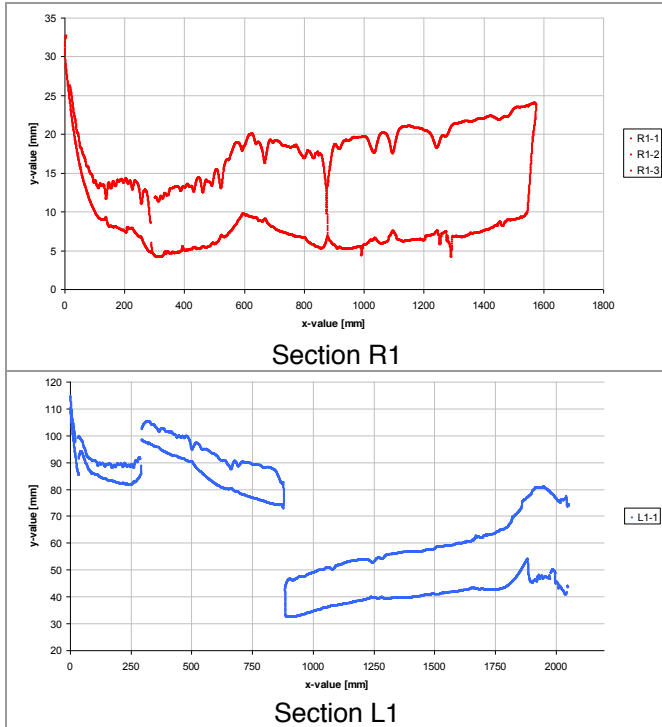


Figure 13. Surface profile of the breakout shell

From the results of the surface study, a hypothetical plane cut can be used in the 3D results to evaluate the shell thickness.

To evaluate the depressions, three of the seven previous sections (from *Figure 10*) were chosen for this plane cut analysis.



*Figure 14. Plane thickness measurement*

In *Figure 14*, the two sections close to the breakout hole, R1 and L1, both show that the thinning of the shell (depressions) comes from the inside of the breakout.

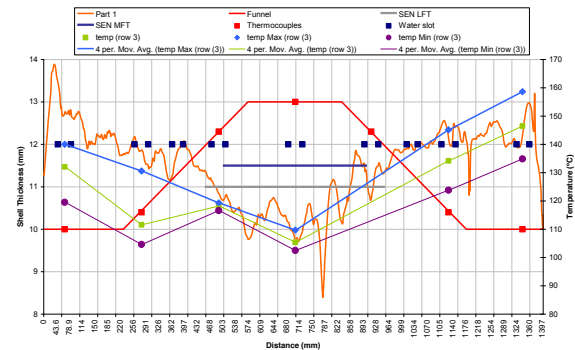
#### *Thermocouples signals*

The thermocouples signals were compared also in this breakout, with the shell thickness on the horizontal plane.

In *Figure 15*, the average value of the thermocouple signals during a period of 3 minutes (green line and green points), maximum (light blue line and light blue points) and minimum values (magenta line and magenta points); are compared with the shell thickness measured in the breakout shell (orange line from *Figure 10* and *Figure 12*).

In the figure the position of the water slots and Berthold sources (dark blue squares), funnel shape (red line), position of the thermocouples (red squares), position of the two SEN's types normally used (Grey and dark blue lines) are also drawn.

From this picture it is clear that the thermocouples signals follows the same trend as the shell thickness. However there is no correlation with the shell thickness or the thinning and the mould features (water slots, Berthold, thermocouples position or funnel shape).



*Figure 15. Thermocouples signals compared with the shell thickness measured.*

## **Discussion of the results**

Considering that the shell thickness in both breakouts follows the same trend as the thermocouple readings, the most plausible explanation for the shell thinning is a low heat conductive layer between the shell and the mould.

If the cause of the shell thinning would be the result of a high steel flow washing the shell from the inside, then the thermocouples would see the opposite trend as seen now, i.e. the signals would show higher temperature where the shell is thinner.

This low conductive layer could be air; where the thermocouples do not register the 'real' temperature of the shell surface due to the isolating properties of this material; and the shell is thin due to the lack of good heat extraction.

## **CON1D simulations**

The heat transfer model CON1D simulates several aspects of the continuous casting process, including shell and mould temperatures, heat flux, interfacial microstructure and velocity, shrinkage estimates to predict taper, mould water temperature rise and convective heat transfer coefficient, interfacial friction, and many other phenomena. The heat transfer calculations are one-dimensional through the thickness of the shell and interfacial gap with two-dimensional conduction calculations performed in the mould. An entire simulation requires only a few seconds on a modern PC [2].

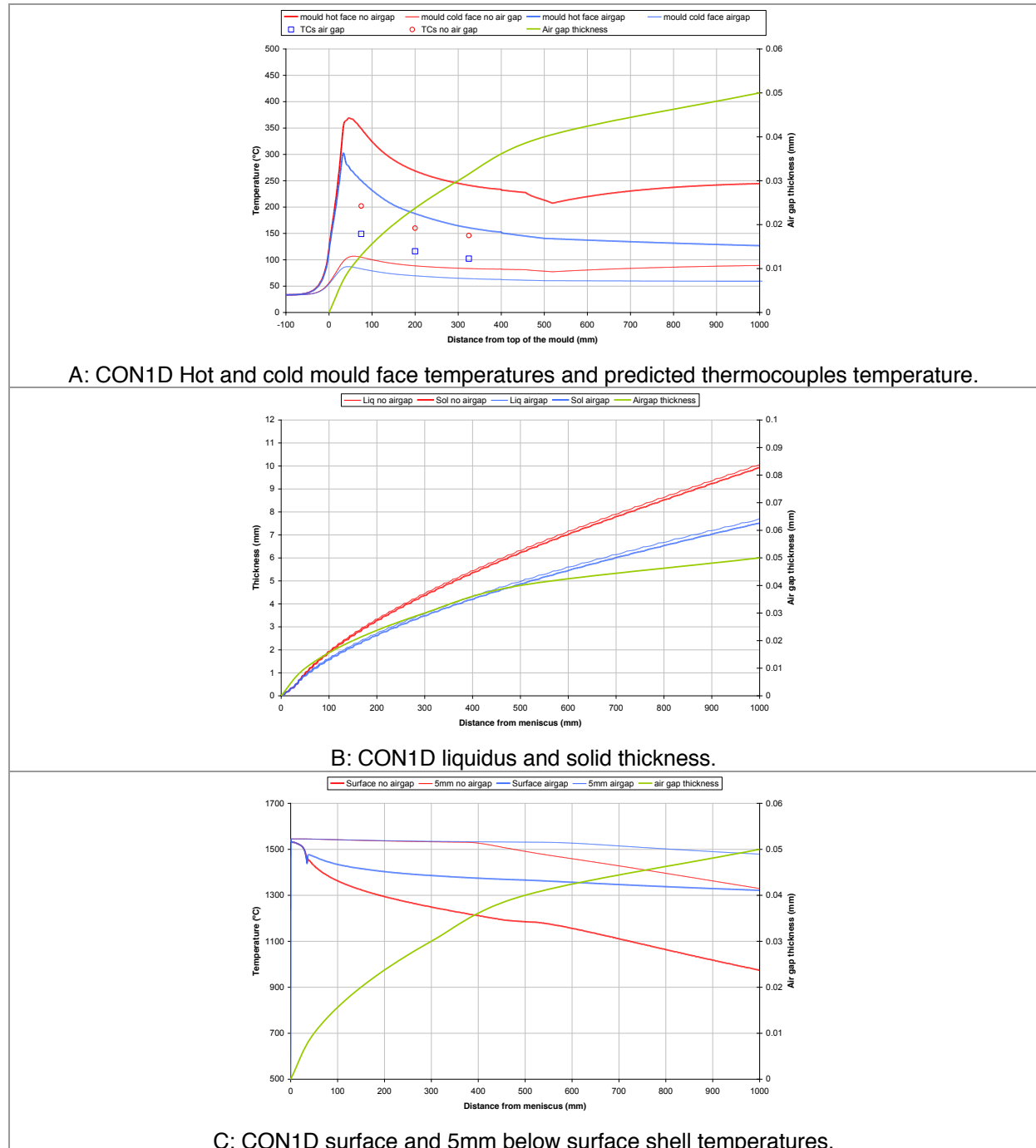
To enable CON1D to accurately predict the thermocouple temperatures, the model was calibrated using a three-dimensional heat transfer

calculation to determine an offset distance for each mould face to adjust the modelled depth of the thermocouples [2].

To verify the theory of a low conductive layer between the shell and the mould; two calculations with CON1D were done with a casting speed of 5.2 m/min, and new mould plates, i.e. maximum copper

thickness. The simulations were done according to the following criteria:

- 1- Simulation with no air gap between the mould and the steel shell;
- 2- Simulation with an air gap following a parabolic increase in thickness from zero at meniscus and 0.05 mm at mould exit (green line in *Figure 16*, secondary Y axis).



*Figure 16. CON1D simulations.*

From *Figure 16* it can be concluded that even a small air gap (maximum at mould exit: 0.05 mm) between the shell and the mould would have a remarkable effect on the solidification.

Due to the low conductive properties of the air (conductivity of 0.06 W/mK), as expected, the mould temperatures in the presence of an air gap will be lower than with no air gap (Red lines for air gap simulation and blue lines for no air gap in *Figure 16*

A); the same behaviour will have the thermocouple signals (red circles for no air gap and blue squares for air gap simulation in *Figure 16 A*)

Consequently, the shell will be thinner when an air gap is present between the steel and the mould (Blue line for air gap simulation and red lines for no air gap in *Figure 16 B*).

Moreover, the surface temperature of the shell in the air gap simulation is hotter than with no air gap; and the temperature 5 mm below surface, as well. In addition, the temperature difference between the surface and 5mm under the surface is smaller in the simulation with air gap than in the no air gap case (Blue lines for air gap simulation and red lines for no air gap case in *Figure 16 C*).

#### Shell thickness prediction

In the CON1D model shell thickness is defined by interpolating the position between the liquidus and solidus isotherms with the temperature corresponding to the specific solid fraction, ( $f_s$ ) equal to 0.1, this fraction is reasonable as inter-dendritic liquid is held by surface tension during draining of the breakout[3].

To compare the predicted steady shell thickness with that of a breakout shell, a correction is needed to account for the solidification time that occurred while the liquid metal was draining during the breakout [3]. Therefore, time in the steady simulation corresponds to distance down the breakout shell according to formula (1)[3]:

$$t = \frac{z}{V_c} + t_d \quad (1)$$

Where:

$t_d$ : drainage time, is the time for the metal level to drop from the meniscus to the breakout slice of interest. [min]

$z$ : Breakout slice of interest [m]

$V_c$ : casting speed [m/min]

$t$ : transient time [min]

Drainage time is calculated based on the Bernoulli equation and mass balance, formula (2)[3]:

$$t_d = \frac{\sqrt{Z_b} - \sqrt{Z_b - z}}{C_D \frac{\pi d_b^2}{4NW} \sqrt{\frac{g}{2}}} \quad (2)$$

Where:

$Z_b$ : Position of the breakout hole from meniscus [m]

$C_D$ : drainage coefficient [-]

$N$ : slab thickness [m]

$W$ : Slab width [m]

$d_b$ : breakout hole diameter [m]

The hole of this breakout was located at the narrow face. Assuming that the steel flow to the mould was shut off simultaneously with the metal level starting to drop below the meniscus and the breakout hole diameter began at 35 mm and linearly grew to 55 mm by the time all the liquid steel had drained. In *Table 1*, the variables used in the calculations are shown.

Variable	Units	
$Z_b$	(m)	1.4
$z$	(m)	From 0 to 1.1
$C_D$		1
$N$	(m)	0.07
$W$	(m)	1.25
$V_c$	(m/sec)	5.2

*Table 1. Variables used for the calculation of the transient time/transient shell growth.*



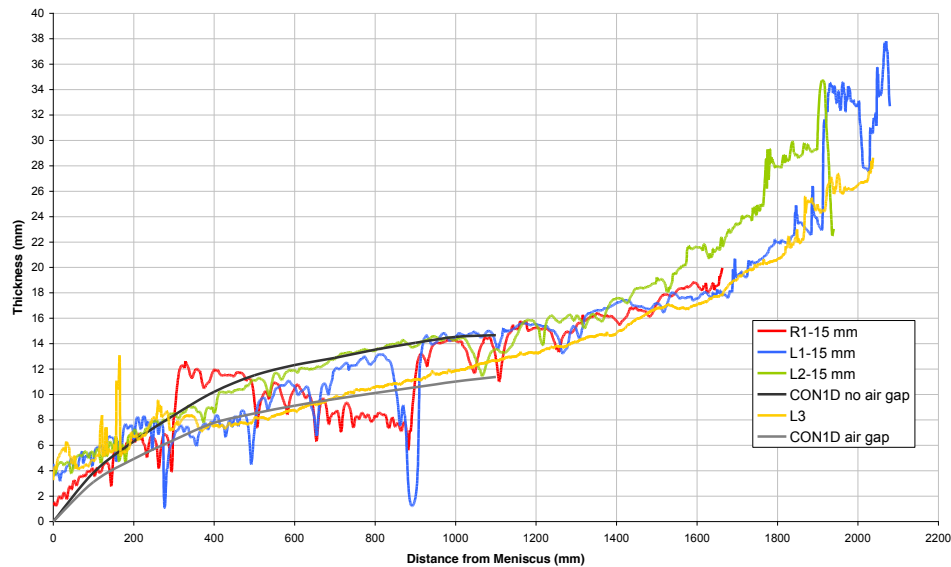


Figure 17. Predicted and measured Shell thickness

Figure 17 gives the predicted shell thickness at both steady state and transient conditions. The generally close match with the transient predictions tends to validate the hypothesis. The underpredicted shell thickness near the meniscus is likely due to a short interval of increased liquid flow into the mould after the breakout started and before level control and flow were shut off. This would have allowed the liquid level to move downward with the top of the breakout shell for a short time interval (not included in the calculations), thus providing additional solidification time at the very top of the breakout shell. This is a very commonly observed effect in breakout shells [3].

## Conclusions

- With the help of the laser thickness measurement technique, it can be concluded that:
- The laser measurements are a valuable tool in measuring 3D thickness profiles of breakout shells.
- Breakout shells have no constant thickness and display three kinds of thinning:
  - local thinning in the longitudinal direction
  - local thinning in the vertical direction
  - thinning in areas of the shell
- Some of the thinnings appear together with longitudinal and transverse cracks.
- The surface of the breakout shell in the outside is smoother than in the inside.
- Shell thickness is related to thermocouple signals, a thinner shell shows low temperature, and a thicker shell shows higher temperature values.

- Even when the cause of the thinnings in the two cases analysed here is not fully understood, it is plausible that an insulating layer (air gap) is placed between the steel shell and the copper mould and that shell thinning is not caused by mould fluid flow.
- There is no perceptible relation between the water slots and/or the Berthold channels position from the mould plates and the thinning of the steel shell.

## References

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