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ADVANCES FOR DC INGOT CASTING: PART 2 – HEAT TRANSFER AND CASTING RESULTS

Gary Patrick Grealy[1]; J. Lee Davis[2]; Einar Kristian Jensen[3]; Per Arne Tøndel[3]; Jürgen Moritz[4]

[1]Corus, Research Development & Technology, Ijmuiden Technology Centre 1970 CA Ijmuiden The Netherlands
[2]Wagstaff, Inc. Research & Development, 3910 North Flora Rd., Spokane, WA 99216 USA
[3]Elkem Aluminium, Research, Aluminium Technology, PO Box 8040 Vaagsbygd, Kristiansand N-4602 Norway
[4]Corus Aluminium Walzprodukte G.m.b.H., Carl Spaeter Strasse 10, Koblenz, D 56070, Germany

Abstract

The continual drive for improvements and advancements in the field of DC sheet ingot casting, and the introduction of casting technologies that provide the user with greater degrees of control over a number of operational parameters, emphasises the need for more in-depth understanding of many related casting fundamentals. This paper will present a study of a number of these fundamentals in two parts. Part 1 will include the influence of metal distribution, while Part 2 will present heat transfer and the resulting solidification behaviour. The results of physical and mathematical modelling and experimental casting trials will be discussed.

Introduction

The challenge with casting large format ingots, especially regarding the control and uniformity of the heat transfer at start and run was recognised as essential to the success of the project. To obtain insight into these phenomena a modelling program was established. The results of that program and the effects on the practical casting application will be discussed.

Practical considerations

From both practical casting experiences and the integrated modelling of the heat transfer, the expectation was for the heat transfer to be characterised by two generally distinct regimes: film boiling during the start and transient portion of the cast and nucleate boiling during steady state. The size of the ingots led to the desire for a starting heat transfer rate in the film boiling regime to reduce the asymmetric bending of the shell (curl) and possible loss of liquid metal containment in the mould[1][2]. Further distinctions in the impingement/stagnation, free falling, and convective, etc. zones are described elsewhere in this paper.

Concerns with a start approach in the film boiling regime are well documented in the literature [1][2][3]. In film boiling, the propensity for ingot cracking increases as does the possibility for shell melting, an over-stated but potentially problematic occurrence. Technologies originally considered for the project – LHC™ and various slot and water hole moulds with pulsed water / CO_2 curl reduction techniques – all had potential for achieving the goal. The LHC mould was chosen largely based on its flexibility in achieving a variety of cooling regimes.

With the LHC technology, film boiling is usually achieved through the application of extremely low water flow rates per linear unit of mould periphery by means of a single array of 22.5° water jets. The start flow rates are usually in the range 0,3-0,4 l/min-cm. Run flow rates are typically between 1,3 - 2,0 l/min-cm. The transition from film to nucleate boiling occurs by increasing the water within the control parameters over the first 40-50 cm of the cast. The transition along the boiling curve from film to nucleate boiling is aided by the application of a primary set of 45° water jets impacting approximately 20 - 25 mm above the secondary jets (centreline to centreline) in an inter-digitated manner [4].

The ability for the LHC mould to function at extremely low water flows for film boiling and extremely high ones for nucleate boiling is well documented[5][6][7][8][4]. This flexibility was required in order to consider the possibility of casting the world's largest aluminium ingot.

Heat transfer modelling

In the modeling of heat transfer, the Alsim casting model was used with boundary conditions as presented by D Mortensen[9]. Lately, also J Grandfield has given a good review of heat transfer formulas used here [10]. The principal outlines can be illustrated in Figures 1-2, giving heat flux as a function of ingot surface temperatures and cooling water temperatures. The curves should be considered approximations only. They are, however, by modelling work proven to give very satisfactory and quantitative reproduction of various observations and measurements made during real DC casting. [2][11]

As indicated by Maenner [12] and others [10], it was useful and even necessary to differentiate clearly between (i) heat transfer in *the impingement* zone, with a potential for an extra heat transfer effect in addition to the heat transfer further down the ingot, re: the upper lines Figures 1 - 2 and (ii) heat transfer in *the streaming water zone* below the impingement with lower heat transfer, re: the lower lines.

The length of the impingement zone and the heat flux intensity depend on several factors like water angle and velocity, cooling spray system, e.g. cooling by water holes or slot, one or several impingement zones etc. as indicated by Wagstaff et al [3]. The chosen zone length determines how much of the impingement (upper) curves which will be realized in the modelling before the heat transfer mechanism shifts over to transfer by streaming water (and heat transfer subsequently follows the lower curves). A length of 12 to 15 mm is predicted by Vader [13] for the water impingement zone associated with each set of LHC water jets, extended by Filipovich et al. even to film boiling [14].

This agrees well with visual observations of the flow pattern and was used for the simulations. The thermal conductivity of the actual alloy also plays a role. Results from bench scale cooling measurements as well as DC casting lend themselves readily to explanation following a suggested changeover from one heat transfer mechanism / curve to another as shown in [5] and [8]. In the present simulations, a relatively long zone length of 35 mm has been calculated and experimentally confirmed to be representative for the cooling in the actual casting with both cooling zones activated in the Wagstaff SplitJet™ Enhanced Cooling Technology.

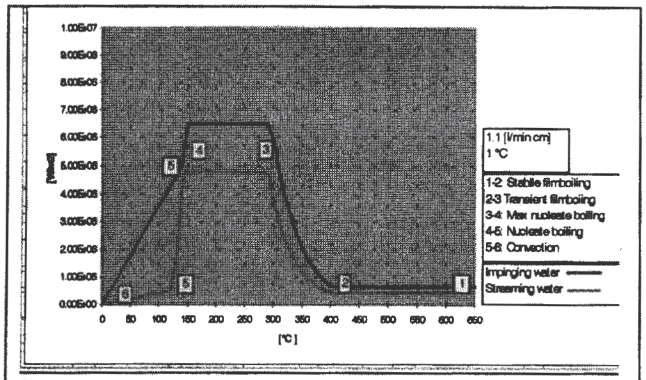


Figure 1a. Heat transfer for low amounts of cold water, 1 °C

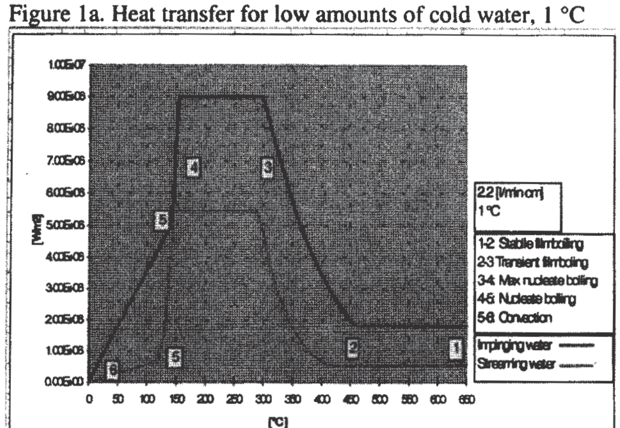


Figure 1b. Heat transfer for high amounts of cold water, 1 °C

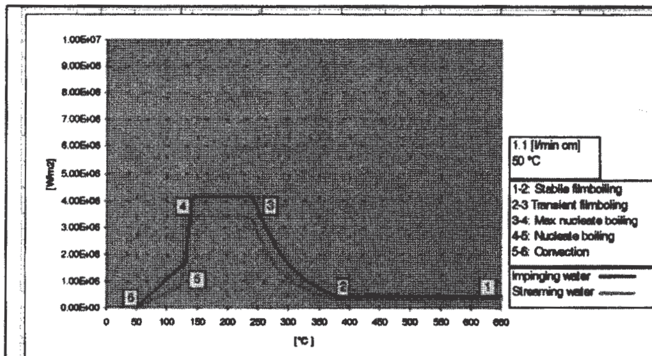


Figure 2a. Heat transfer for low amounts of warm water, 50 °C

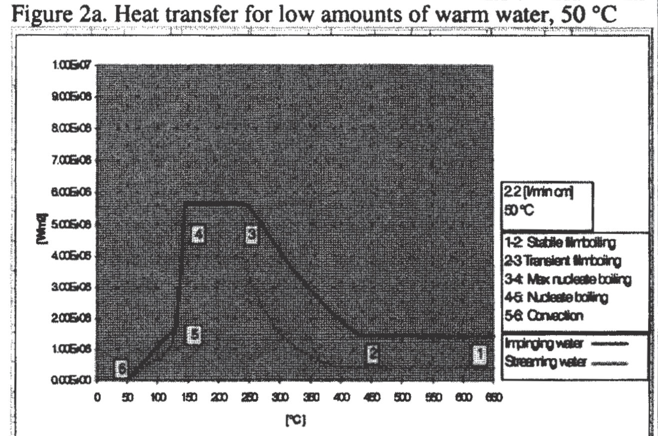


Figure 2b. Heat transfer for high amounts of warm water, 50 °C

Applying a separate set of formulae to the impingement zone also makes it relatively simple to account for a possible dip in the temperature profile locally. The "boxed" numbers at the curve-breaks denotes the classical changes in the heat transfer. Starting with high surface temperatures just below the mould exit, and proceeding in the casting direction towards lower temperatures, the numbers have the following meaning:

Section 1-2 marks a zone of stable film boiling, 2-3: transient film boiling, 3-4: a maximum level for heat transfer by nucleate boiling, 4-5: decreasing nucleate boiling when approaching the boiling point and 5-6: heat transfer by convection. Comparing Figures 1a with 1b, note that increases in both of heat transfer rate and the Leidenfrost temperature are predicted with increasing amounts of water, especially for the impingement zone. A correct description of this dependency is vital for satisfactory modeling of all possible film boiling situations and for the development of butt curl in the starting phase of casting.

The same trends are evident in Figure 2 as in Figure 1, though the heat transfer levels are generally lower due to the higher water temperature specified in the calculations here. It has to be stressed that the curves shown are valid only for those ingot positions with a corresponding, local water temperature. Thus Figures 1a and b would be more representative for the situation at the newly emerging part of the ingot when the initially relatively cold water hits the ingot surface. Figures 2a -2b would then be more representative for the situation further down the ingot when the cooling water has reached higher temperatures.

Different parts of the ingot would experience heat transfer according to curves somewhere in between the two "extremes" mentioned, depending on the actual water temperatures at the various positions on the ingot. Therefore, also the level of seemingly constant maximum heat transfer would in general lead to slopes of decreasing heat flux when plotted as function of increasing distance from the impingement point. In general, measured values typical for the middle phase of casting as determined by various laboratory experiments agree well with the lower curves shown here.

For the occurrence of film boiling, the following is considered the most important: besides low impingement effect by using suitably low amounts of water in the starting phase (Figure 1a) and suitable cooling efficiency of the water (properties/ cleanliness/ impurity content of the water) naturally also the heat input is important (casting speed and temperature, filling rate and ramping up of casting speed and amount of cooling water in the starting phase). Extensive fine-tuning of the latter parameters as well as metal level was necessary during the DC casting in order to control satisfactorily the starting phase as well as the dynamic equilibrium phase of casting.

An example of the predicted surface temperatures and heat transfer is shown in Figures 3a and 3b for the starting phase of 600x2400 mm ingot alloy 5083 as a function of distance from the top of the mould and time since start of mould filling. On Figure 3a the surface temperatures in the casting direction along the central part of the rolling side of the ingot are shown at various points in time. Figure 3b presents the corresponding heat fluxes. At first, the temperature lines of Figure 3a move to the right in the figure with increasing time (curves a-g). In the time span from about 300 to 460 s after filling the mould, there is an increasing dip in the temperature curves in the impingement zone, curves (a-e), 0.125-0.160 m from the top of the mould. The heat flux is about 1 MW/m². Further down the ingot (to the right of the dip), there is a zone of slightly decreasing high temperatures in the range of 500 - 400 °C, expanding as the ingot length increases and denoting a period of film boiling. The heat flux in this zone without any impingement effect is about 0,3 MW/m². At 440 s, curve (f), and 460 s, curve (g), the temperatures at the bottom of the dip have reached about 100 °C, i.e. no film boiling occurred anymore in this range.

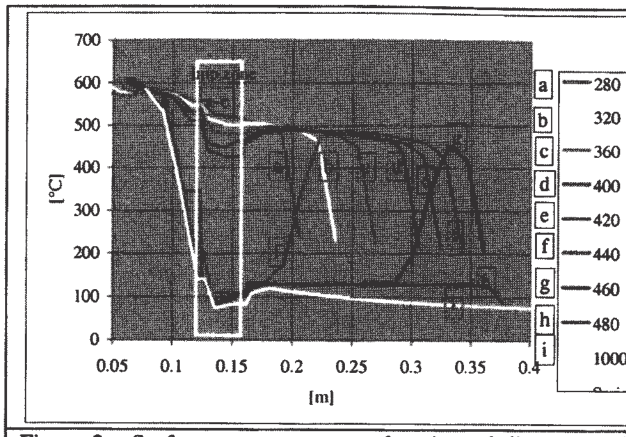


Figure 3a. Surface temperatures as function of distance and time, alloy 5083, 610x2400 mm

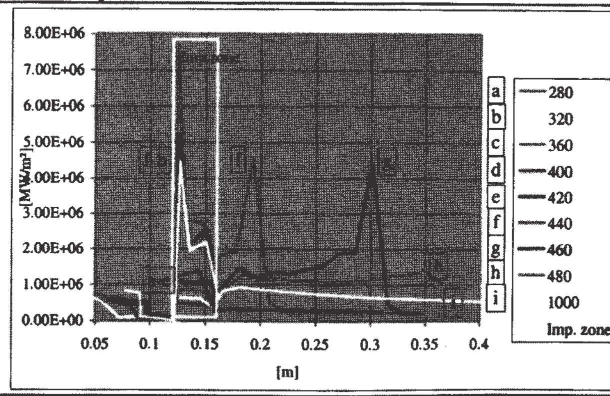


Figure 3b. Heat flux as function of distance [m] and time[s], alloy 5083, 610x2400 mm

Consequently, there are very high heat fluxes in the beginning of the impingement zone, of the order of 7 MW/m². There is now a marked widening of the bottom of the dip. The upper limit of the film boiling area is clearly moving down on the ingot. Below the impingement zone, there is first a peak value of ~4 MW/m² for the two curves (f) and (g), indicating the maximum level for the streaming water zone, re: Figures 1 and 2. Then film boiling disappears completely at 480 s (curve h).

Instead the cooling curve has now returned to the left and taken a position and shape typical for cooling without film boiling (compare with curve i at 1000s and convective cooling). The high temperature levels in the film boiling period have now been replaced with a level of about 120 °C. There is a long zone with nucleate boiling at a heat flux of about 1 MW/m². At later stages, cooling by convection takes over below the impingement zone, as shown by curve (i) at 1000 s.

Figure 4a is a model "snapshot" of the rolling face surface temperatures at 440 s. The dome shaped area denotes the remaining film boiling area at this point in time. The film boiling area is diminishing with time, both from the top and from the sides of the visible "dome." The lower half of the figure is the still relatively cold starting block. On Figure 4b the heat fluxes at 440s are given which correspond to the temperatures in Figure 4a.

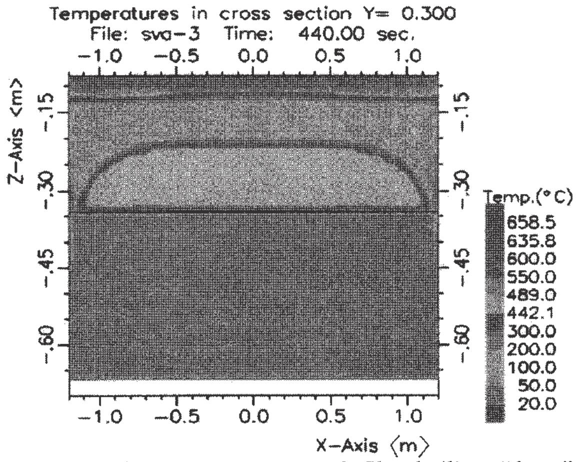


Figure 4a. Surface temperatures and film boiling "dome", 610x2400 mm model ingot rolling side at 440s, alloy 5083

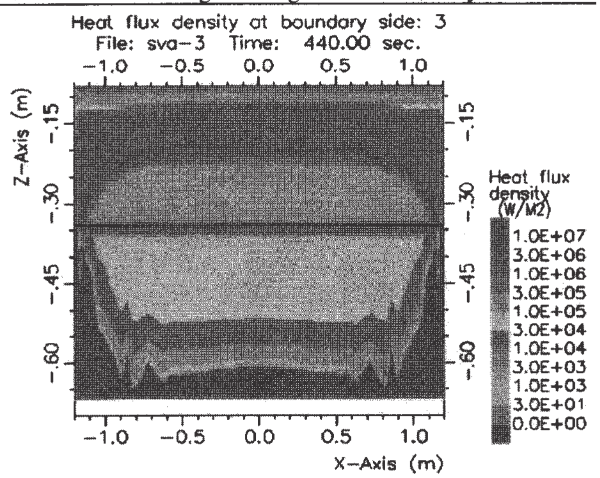


Figure 4b. Heat flux, 610x2400 mm model ingot rolling side at 440 s, alloy 5083

Butt curl modelling – trend analysis

In an effort to predict butt curl development and foresee possible related safety and quality difficulties [15][16][17], a trend analysis was performed through model iterations of the butt curl as a function of increasing ingot width. The study was made by coupled thermo-mechanical calculations using the Alsim-Alspen casting models respectively [18][19]. To simplify the calculations, liquid flow in the sump was in these cases neglected. It has been verified later that this simplification does not change the conclusions of the trend analysis. The physical properties of the alloy were calculated by the micro-structural model Alstruc [20]. Calculated liquidus and solidus temperatures are 635 °C and 489 °C respectively for a chosen alloy of AA5083 composition. Mechanical properties used were those measured in the international research project Empact[21]. The results are summarised in Figure 5 for a nominal ingot thickness of 600 mm and ingot widths of 1685, 2000, 2400 and 3000 mm as shown by the curves A-D respectively. It is indicated that the development of the butt curl would level off after about 1400 s.

When using suitably low amounts of water and ramping-up procedures in the starting phase, the butt curl is predicted to increase with increasing ingot width in a regular manner but only to relatively low final values. This is the case even for the 3000 mm wide ingot. The very marked initial peaks and fallback for the butt curl for all the low-water curves are probably associated with changing cooling conditions on the rolling side of the ingot.

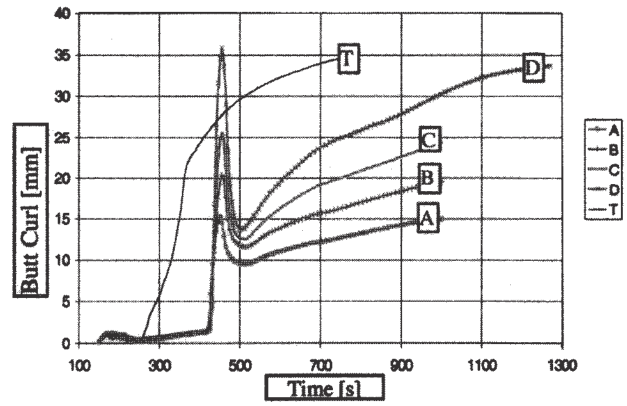


Figure 5. Butt curl as function of 600 mm ingot widths over the range 1685-3000 mm

There is a drastic change of cooling as the early film boiling breaks down and the much more severe cooling by nucleate boiling takes over. In order to reproduce by modeling the low water butt curl observations made initially during the first castings of the 1685 mm ingot, it was found absolutely necessary to fine-tune the cooling conditions specified. In particular, the observed initial film boiling period and development had to be reproduced in the calculations. In contrast to this, a much larger amount of butt curl results from rapid cooling when using full amounts of water (nucleate boiling start practice) as can be seen for the 600x1685 mm ingot *curve T*. For *T*, there is no initial peak and the end value is predicted to be higher than the 3000 mm ingot start in film boiling.

Ingot flatness

To minimize ingot geometry deviations an empirical formula (1) was employed from Håkonsen[22].

$$D_M = C_1 D + C_{alloy} \Theta V D^2 \qquad (1)$$

It was used to calculate the mould opening D_M, where C_1 is a thermal contraction constant, D is the resulting nominal ingot thickness, C_{alloy} is an alloy constant and V is the casting speed. In the initial empirical model for 610x2400 mm, the form of Θ was a *sine* curve, later modified for the largest formats to Håkonsen's Arrhenius version (2):

$$\Theta = 1 - \exp\left[-1{,}9 \cdot \left(X^A\right)^{1{,}9}\right] - \exp\left[-1{,}9 \cdot \left(\frac{W}{D} - X^A\right)^{1{,}9}\right] \qquad (2)$$

Casting results

The Casting Team established by the Partners had the responsibility to obtain, in order of priority: no full-length cracks, best short face (i.e. shoulder, edge, end) and rolling side surface finish and near-surface structure, and optimal geometry.

Cracking

LHC mould technology was chosen on the basis of flexibility in cooling regime, and secondarily on its ability to produce consistent final ingot product (shell zone, grain size, etc.) However, in the early development work for this programme and others at Mosjøen on common tooling sizes (600x1685 mm, 610x2000 mm), the failure mode during start-up was *cracking*.

The cracking appeared to be due to the transition from film to nucleate boiling, perhaps exacerbated by the change in the thermal profile of the ingot and its near surface areas during the LHC Split-Jet valve opening. During this casting phase, the primary water jets hit the shell of the ingot and establish the advanced cooling distance above the previous level of the secondary jets. Almost instantaneously the water velocity of the 22° secondary jets goes from 1,5-2,0 m/s to 0,8-1,0 m/s and water patterns for both primary and secondary jets temporarily interact to further disrupt the uniformity of the resulting heat transfer. Prior LHC casting had shown little cracking effect from this transient, despite it's apparent severity. In Mosjøen, however, this formed the first barrier to success.

Mosjøen personnel finally breached the roadblock through clever practice development. Under these conditions, film boiling was a reality at selected start speeds in line with predictions from the mathematical modelling. The tooling also allowed us more than sufficient water values to run the ingot within the direct chill nucleate boiling regime as discussed in the modelling section. The consistency of the water application shown in Table 1 turned out to be a very important consideration as we began to deal with the practicalities of successfully starting the large format ingots.

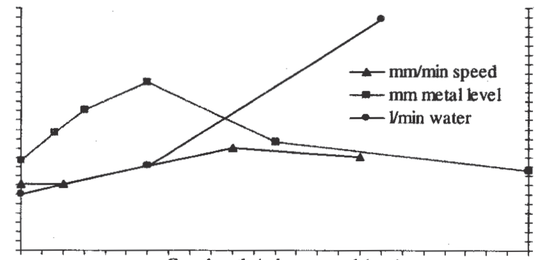
Table 1. Variability in Wagstaff Mould Water Flows

Mould Type	Pooled 3-Sigma Values for Flow* (nominal values in litres/cm-min)
LHC	0,9 ±0,35 % of nominal (0,48) 1,02 m/s
Conventional	5,6 ±3,54 % of nominal (1,03) 1,10 m/s

Curl Control, Butt Deformation

The results predicted by the modelling indicated that there would be no significant increase in butt curl with increasing ingot size as long as the ingot start was in film boiling. The most practical interpretation of the butt curl "peak" in the model results Figure 5 seemed to be a collapsed butt defect. Experience with casting Al-5Mg alloy indicated that most of these collapsed butt defects would "heal" with conventional ingot sizes. Would the same be true for the large format ingots, and if so, how long would the cracks be? Would the length of the discarded butt zone be acceptable? At 4,5 tonnes per meter of cast length, this was a costly and risky question. Casting parameters were required to safely begin the campaign. Once a safe recipe was established through trial-and-error application of sound casting principle, a designed experiment would be run to determine the realistic boundaries of the "casting window."

* 20 moulds selected at random (n=8 measures for each mould)



Despite the descriptive modelling work described in this paper, there was (and still is) a difficulty in DC casting: getting the theory and models to link directly to recipe parameters. Wagstaff has an empirical model for development of LHC casting parameters with 10 fundamentals e.g. ingot size, aspect ratio, solidification range, thermal conductivity, water characteristics of the LHC mould, etc. This capability combined with modelling and prior work by Elkem allowed an initial recipe to be prepared in advance of the first trials per Figure 6.

Figure 6. Parameters for first 610x2400mm resulting in 60 cm length, collapsed butt, no full-length cracks, & superior surface

The initial parameters proved to be successful and exploration of the casting window began in two segments: start-phase and run-phase. The main start phase response variables were steam line behaviour, cracking and butt stability on the starting head. Run phase responses were surface quality and ingot geometry. The work in 610x2400 mm ingot development and the designed experiment that ensued were statistically significant in a number of areas, particularly steam line length† versus crack length[23]. During these trials, it became apparent that the large format ingot's failure mechanism was actually a collapse of the shell supporting the butt due to the weight of the ingot. When the ingot was in film boiling for a relatively long duration at the cast start, 7-10 "thin collapse" cracks and perhaps 0-1 larger collapse cracks occurred on each long face of the ingot, making an aesthetically pleasing butt shape, low butt swell, etc. Figure 7.

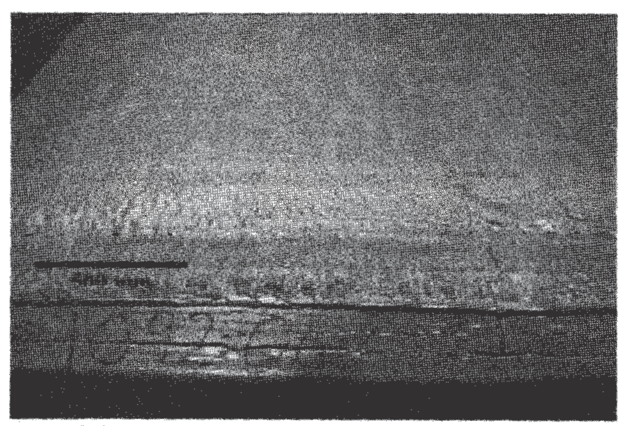


Figure 7. Typical butt zone large format LHC ingot; five "thin

† The steam line length is the cast length at which film boiling is completely replaced by nucleate-boiling on all parts of the ingot

collapse" cracks are not visible in this photo, only 1 larger type. With this approach, there was little secondary butt curl and no real measurable primary curl either. During the transition from primary to secondary curl – at the onset of the steam line devolution from stable to unstable film – the ingot would break/crack under it's own weight / contractive stress, and in doing so would relieve the various stresses associated with starting phase. By 50 cm cast length the ingot had 35-50 mm of "curl" at the centre of each short face despite the complete collapse of the butt, similar to the model results from Figure 5.

According to the statistical results presented in this paper, and verified by experience over the campaigns, the price of the nice looking butt geometry was external (and internal) crack length. Figure 8 shows that – inside the recipe paradigm – steam lines are inversely proportional to the *water ramp rate*, and Figure 9 shows that external crack lengths of the large format ingots are smallest (best) when the *water ramp rate* is high[23][24]. In attempting to drive crack lengths to a minimum by increasing the water ramp rate, film boiling (at cast start) could easily be destabilized with a resulting compromise in butt geometry.

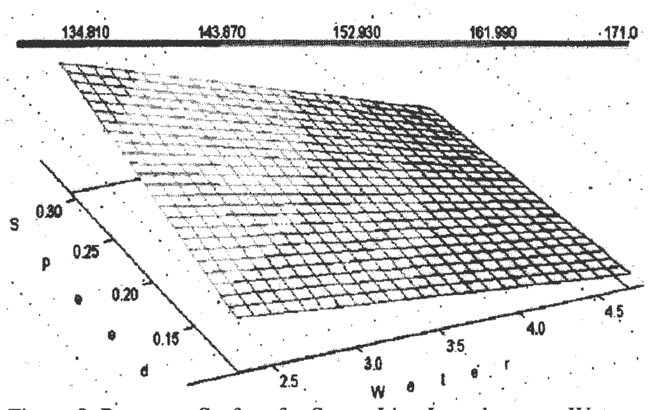


Figure 8. Response Surface for Steam Line Length versus Water and Speed Ramp Rates, 610x2000 mould. $R^2 = 0.95$

This appeared to have no detrimental effects at first, since internal crack lengths shortened from 40-50 cm to 25-30 cm on the 610x2400 mm format. However, in casting an ingot longer than 4 meters, the butt stability was seriously compromised when the steam lines along both rolling faces were irregular. A 15-20 mm shift in the butt was experienced on two different large ingot formats due to the settling of the ingot on an asymmetric butt shape in the starting head.

When steamlines are uniform, the contraction is uniform as shown in Figure 10. Since the shell is relatively thin, the collapse of the butt is also uniform, and the entire ingot sits on the raised centre portion of a modified flat dish starting head. When sections of the steam line break down >20 mm different in cast length, then the sections in/out of film boiling contract at much different rates, causing tremendous strain on the areas still in film boiling. The strain is sufficient to pull these "hot" areas off the starting head and towards the centre of the ingot. In large format ingots one can often observe this phenomenon as a *negative butt curl*, where large sections of the rolling face bend in the direction opposite of 'normal' as if they were beams *completely distinct* from the rest of the ingot.

This serves to rapidly destabilise the butt, and can even lead to severe external cracks that run the full length of the ingot. This was found to occur for recipes with statistically low *average crack* lengths e.g. the failure mode of casts with recipe type for very low crack lengths was catastrophic not continuous.

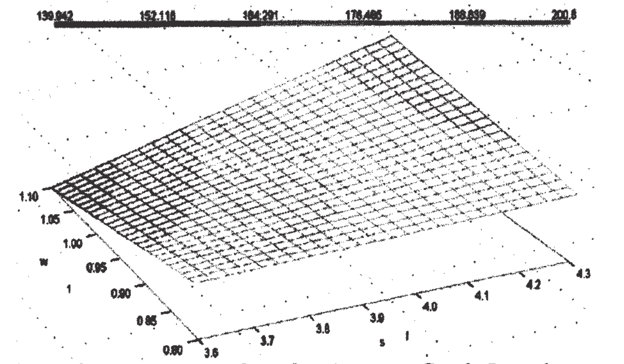


Figure 9. Response surface for Average Crack Length versus "water ramp", "starting head fill rate", and the interaction term for the two, 610x2400 mm mould. $R^2 = 0.87$

After a number of full-length casts, a preliminary rule on butt stability and crack length of the large ingot formats was decided: assure a process with uniform and full steam line and measure on the product less than 10 mm separation from the centre of each rolling face and the starting head by 30 cm cast length. Failure to follow this rule can lead to defects, as in Figure 11.

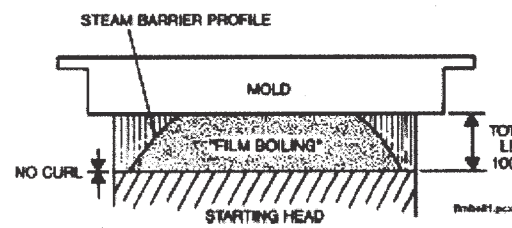


Figure 10a.

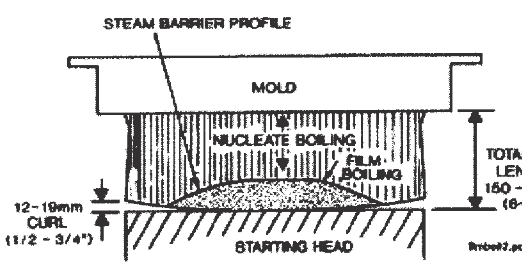


Figure 10b.

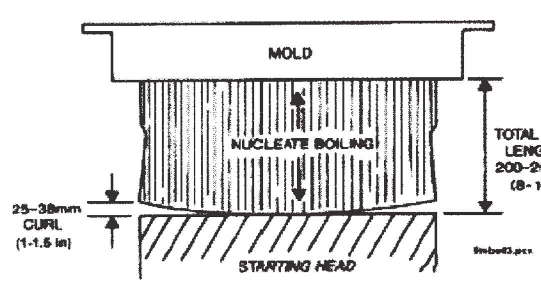


Figure 10c.

Figure 10. Dynamic evolution of steam line in response to ingot surface temperature during a film boiling ingot start.

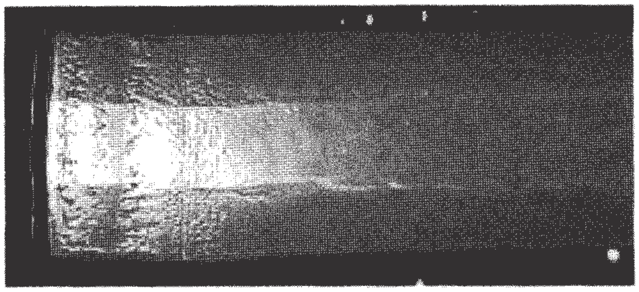


Figure 11. Bent 610x2400 mm ingot from shifting on an asymmetric base. The instability was caused by a steam line evolution 50 mm different from one rolling face to the other.

Figures 10 a-c also describe snapshots of the dynamic behaviour of the element that most visibly describes the heat transfer process in DC casting – the steam barrier AKA steam line or film boiling area. We can see from these figures that the shape of the region experiencing sub-film dry-out has the same dynamic shape as that predicted by the model Figures 4a-b.

Ingot Shape Control

The modelling section detailed the appropriate theoretical considerations. Wagstaff, Inc. has a proprietary empirical model based on Weaver et al[25] for calculations of mould bore openings. Constants and conversions from this Wagstaff code were used in the project along with refinements in the fundamental form of the equation as previously described in this paper, the end result being exceptionally uniform and flat ingots.

As one increases the width of an ingot, the dimensional consistency of the thickness becomes more critical in scalping. All defects must be removed with minimal metal loss in order to reduce queue time, machine wear, and motor load on the scalper as well as scalper chips which are to be remelt in the casthouse. Initial project results in Figure 12 from the 610x2400 format showed a "W"-shape in the ingot thickness. This originated from the sine form of the equation for the mould bore opening.

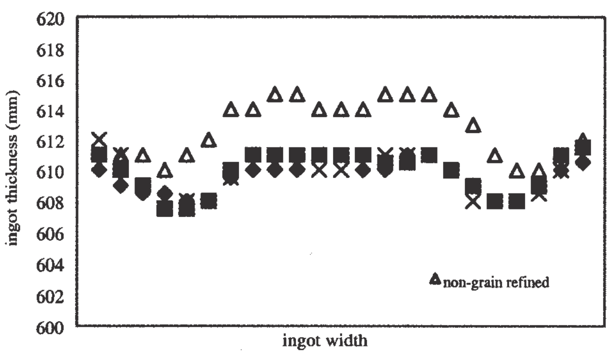


Figure 12. 610x2400 mm ingot thicknesses at steady state

The "dip" in the thickness at the quarter points of the rolling face had to be eliminated. Utilizing data from the 2400 ingot casting as well as the new form of the mould bore opening criteria described earlier, the 2700 mould bore was designed to create a 2700 ingot thickness with continuous curvature as shown in Figure 13. This 610x2700 ingot is close to "dead flat" and could be adjusted by speed, impressive for a 2,7 m span.

There was a small error in conversion of the constants from the old model to the new, which led to the slightly thicker centre portion of the rolling face. For the 610x2700 ingot, the ingot thickness was 612 mm (with normal grain refining practice) instead of the 610 mm centre thickness desired.

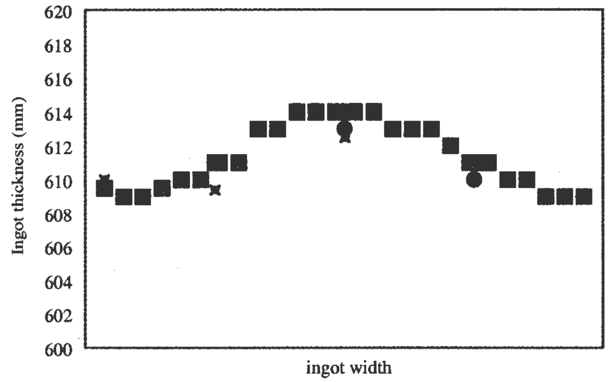


Figure 13. 610x2700 mm ingot thickness at steady state

According to the regression found in Figure 14, the error in design speed was around two mm/min. This also implies that the hydraulic control system, as a whole, should be capable of controlling the true speed to ± 0,2% of the target value. This is an unlikely (see Figure 15) but important consideration, as absolute ingot geometry becomes an even more critical input to statistically controlled and capable hot mill processes.

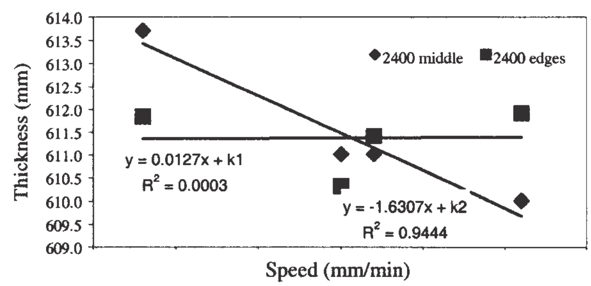


Figure 14. Ingot thickness versus cast speed for 610x2400 mm

From modelling and experience, we knew that the control of the butt swell would not be effectively achieved without film boiling start techniques. In practice, we found that the recipes that produced consistent, uniform steamlines and stable butts were also extremely successful in retarding the amount of butt

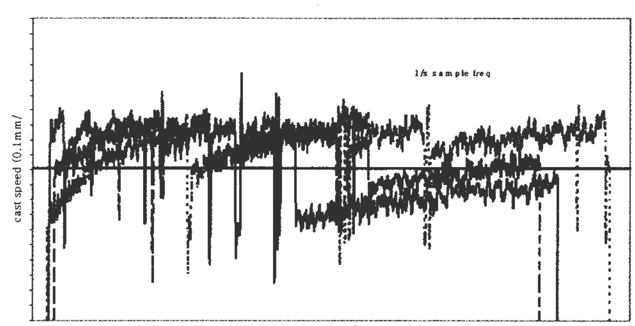


Figure 15. Minor Variations in Cast Speed vs. Set-point

swell. Total butt swell at the saw cut was only 8-16 mm in excess of the nominal thickness and the maximum swell observed was on the order of 638-640 mm as seen in Figure 16. The maximum mould bore opening was 660 mm, so the minimum contraction in the centre of the long rolling face thickness was 3,5%. The maximum contraction at steady state was approximately 7,6%.

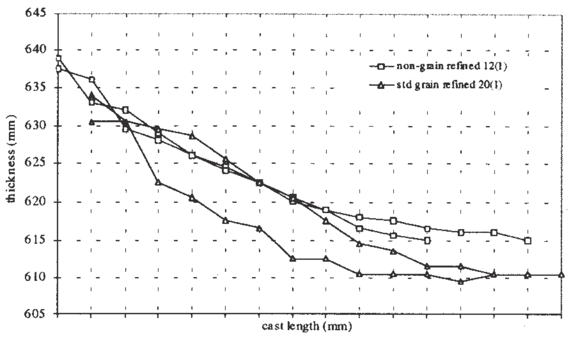


Figure 16. Thickness over length (e.g. swell) 610x2400 mm

Final conclusions

With the application of modern modelling techniques, we obtained a more in-depth understanding of the influence of heat transfer in the start and steady state phases of a cast. Through practical casting experience we were able to apply this increased understanding to cast the world's largest aluminium rolling ingot. Key points in this process included:

- By fine tuning the *starting parameters* like ramping of the amount of water, the cooling in the impingement zone, metal filling and strict level control and lowering rate, a safe starting practice was found that gave good reproducibility of the starting phase with very low butt curl, good butt stability and well controlled starting cracks.

- The measured development of the *butt curls* as well as final values agree very well with the predictions of the mathematical modelling work though the latter does not take the observed starting cracks into account.

- By likewise fine-tuning a number of measures and having a strict control over the variations in the *static phase* of casting, a smooth LHC surface with a minimum sub surface segregation was obtained. The critical parameters include the metal level and level control, metal distribution, temperatures along the ingot circumference in the mould and heat transfer.

- Measurements and modelling simulations confirm that a satisfactory circumferential temperature distribution was obtained.

- Except for buoyancy-related effects, there is very good agreement between the water modelling, the mathematical modelling, and the actual temperature measurements.

- The improved formula and constants used for calculating the *mould bore* resulted in an ingot deviating smoothly by ~ 2 mm from a perfectly flat rolling face.

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