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IMPACT OF WATER HEAT EXTRACTION AND CASTING CONDITIONS ON INGOT THERMAL RESPONSE DURING D.C. CASTING

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Abstract

Water cooling during the start-up phase of the cast is one of the major parameters which affects casting performance, along with heat input (casting speed, metal temperature), and primary and bottom block cooling. Water cooling depends on the ingot surface finish and temperature, the casting parameters (water flow rate and temperature, mould technology) and water quenching ability. This paper describes the method used to determine the heat transfer coefficients for some of the above parameters (surface temperature, water flow rate and temperature, pulsation characteristics). The influence of the casting parameters on ingot thermal response is then predicted using Alcan's finite volume transient casting model, with the purpose of better understanding and controlling the D.C. casting process.

Introduction

The temperature distribution and thermal history of the DC cast ingot are responsible for the majority of the phenomena which occur during the cast (surface quality, microstructure, butt curl, hot cracks and hot tears). The thermal history depends on the casting parameters used during a cast. These parameters define the heat input and heat sink that will finally result in the thermal profile of the ingot. The heat input is mainly controlled by the metal pouring temperature, filling practices and casting speed, while the heat sink depends on the mould technology, the water flow rate and impingement angle, the water quality, start-up technologies such as pulsed water, and the heat extraction through the bottom block. This paper deals with the determination of the water heat extraction characteristics (heat transfer coefficients) and the effect of some of the casting parameters on the ingot thermal response. This was performed using a 2-D transient casting model. This computer based analysis results in a deeper quantitative understanding of all the related influences of casting parameters on the ingot thermal profile. The final objective of this work is to broaden the operating window to obtain defect-free ingots by using a more fundamental quantitative tool rather than the present situation where trial and error is mainly used to reach this objective.

Heat Transfer Characteristics Related to Direct Chilled Cooling

There are four modes of heat transfer between water and a hot surface [1,2,3]: stable film boiling at high temperatures (350°C and more), transition boiling (200 to 350°C), nucleate boiling slightly above 100°C, and finally convective heat transfer. These modes can exist simultaneously during the cast start-up at different locations on the ingot surface. Figure 1 shows schematically the main heat extraction sequence that occurs during the start of a cast. As the water touches the ingot, a relatively strong film boiling mode prevails in the impingement region and water is ejected away from the hot surface. As the cooling progresses, film boiling will be gradually replaced by nucleate boiling at the impingement point. At this moment the film of vapor will begin to move downward at a certain speed to finally completely disappear over the lower surface of the ingot that will be cooled by nucleate boiling and convection. At this moment the surface thermal history of the ingot will almost be stable, even if the steady state phase of the cast (complete sump formation) is not yet reached.

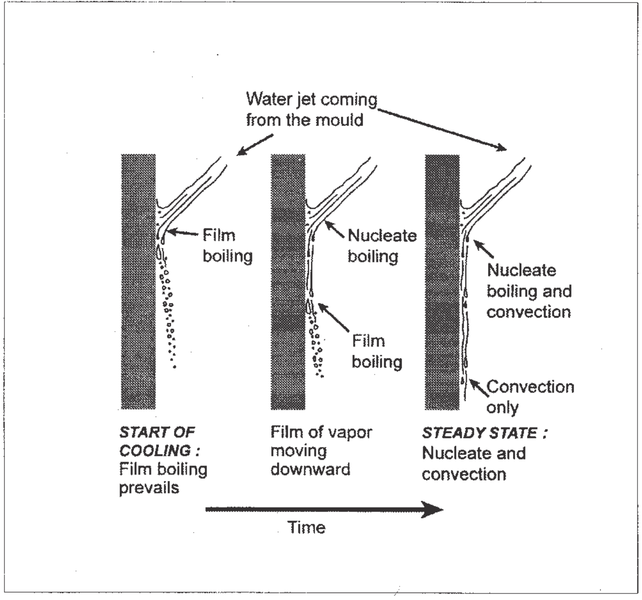

Figure 1: Evolution of a film of vapor on ingot surface at cast start-up.

All these mechanisms of heat transfer are intimately linked with the jet characteristics (flow rate, thickness, velocity and angle, the water quality and the ingot surface finish).

Experimental Rig to Determine Heat Transfer Coefficients

The heat transfer coefficients were experimentally determined for a wide range of water flow rates, water temperatures and pulsing parameters (start-up technologies) typically used in a casting plant. The experimental rig used to determine the heat transfer coefficients is schematically described in figure 2. It consists of a test block equipped with thermocouples and heated to 550°C. Cooling is performed with a typical section of a DC mould positioned in front of the test block. The water flow rate is adjusted to the desired values with control valves and a magnetic flow meter. For some tests, a pulsation unit, along with pneumatic valves, was used to produce the on/off pulsation of the water at the cast start-up. The water temperature from a heated reservoir could also be adjusted. A silver block was used to reach higher starting temperatures (550°C) and a comparison was made with different as-cast aluminum blocks.

Temperatures from the imbedded thermocouples were recorded at a frequency of 40 Hz with a data logger and a PC. An inverse conduction technique [4,5] was applied to back-calculate the heat transfer coefficients from the recorded temperatures.

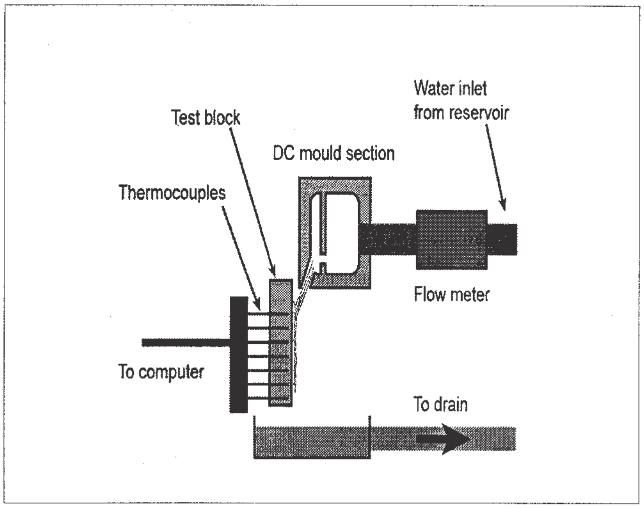

Figure 2: Experimental rig for heat transfer measurements.

Influence of Casting Parameters on the Heat Transfer Coefficient

Figure 3a) shows typical cooling curves with a continuous water flow at the center of the impingement point and 50 mm below. The corresponding heat transfer coefficient evolution is shown on figure 3b) where the heat transfer coefficient has been normalized by the critical heat transfer coefficient at the impingement point. The main heat transfer characteristics extracted for each test are presented in figures 3a) and 3b). They are the Leidenfrost temperature (T_L, temperature at which stable film boiling is gradually replaced by nucleate boiling) and related heat transfer coefficient (H_L), the critical nucleate boiling temperature and heat transfer coefficient (H_C and T_C). The heat transfer curves are very similar to those obtained with pool boiling, apart from the start of the quench where film boiling requires a certain time to establish itself. The temperature at 50 mm below the impingement point decreases slowly mainly due to conduction inside the block, the water being ejected away at the impingement point due to the formation of film boiling.

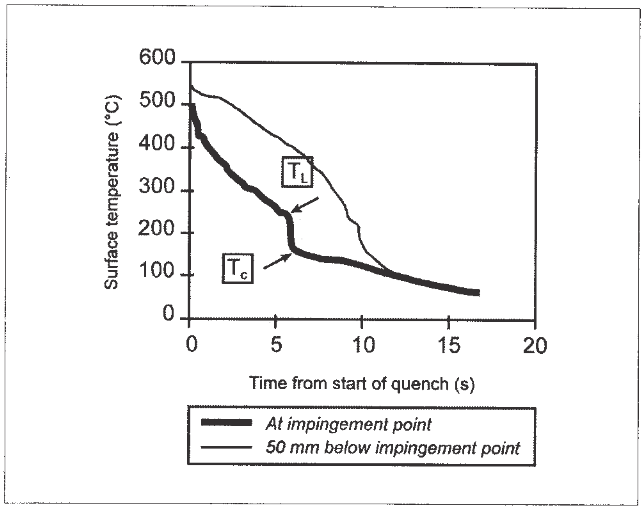

Figure 3a): Typical cooling curves in the impingement region.

In figure 3b) the heat transfer coefficient at 50 mm is very small for a long period of time due to the lack of direct water contact. As the temperature decreases at the impingement point, the film of vapor will gradually move downward, as it is replaced by nucleate boiling. The heat transfer coefficients at 50 mm will rapidly increase when the water curtain passes over this location as seen in figure 3b).

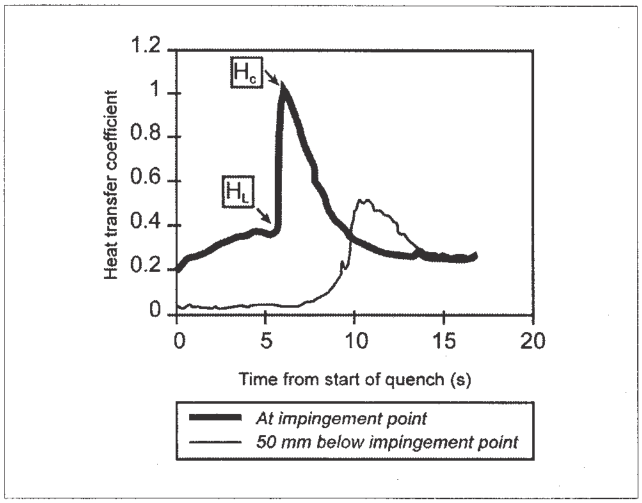

Figure 3b): Typical heat transfer coefficients in the impingement region.

The variation of the heat transfer coefficient near the impingement point is highlighted in figure 4, where the normalized critical nucleate boiling heat transfer coefficient is plotted as a function of the distance from the impingement point. It is low in the region of the back flow above the impingement point, and then it increases rapidly to a maximum value corresponding to the location of the jet's maximum momentum [6,7]. Finally the heat transfer coefficient decreases rapidly to an almost stable value in the free falling film region.

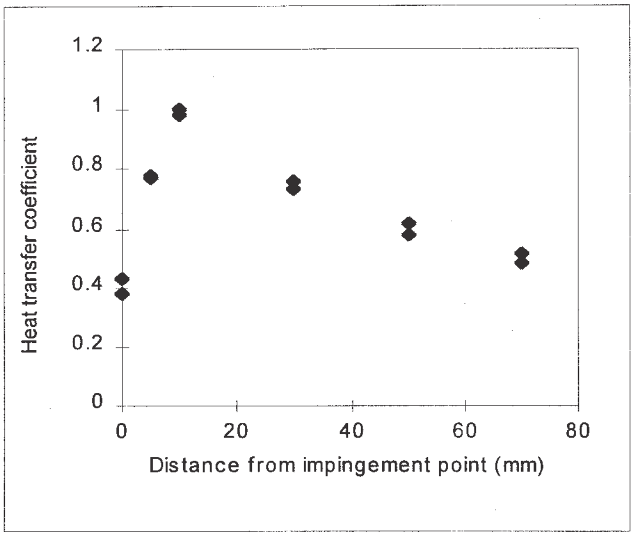

Figure 4: Variation of critical heat transfer coefficients with the distance from the impingement point.

The effect of the water flow rate on the normalized Leidenfrost temperature is shown in figure 5. The effect shown in this figure combines the effect of higher flow rate and higher velocity (jet momentum) since the jet thickness was the same for each level tested. The flow rate in this figure was normalized with respect to a typical value used in a cast house. It can be seen that this temperature increases almost linearly with the flow rate. The Leidenfrost temperature is important as it partly controls the moment at which the heat transfer mode will switch from film to nucleate boiling, leading to rapid cooling of the ingot. This implies that the flow rate at the cast start-up must be maintained low during continuous water flow cooling in order to keep the ingot relatively hot for a certain period of time in order to avoid cooling and stress build-up which could lead to ingot cracking and severe butt curl.

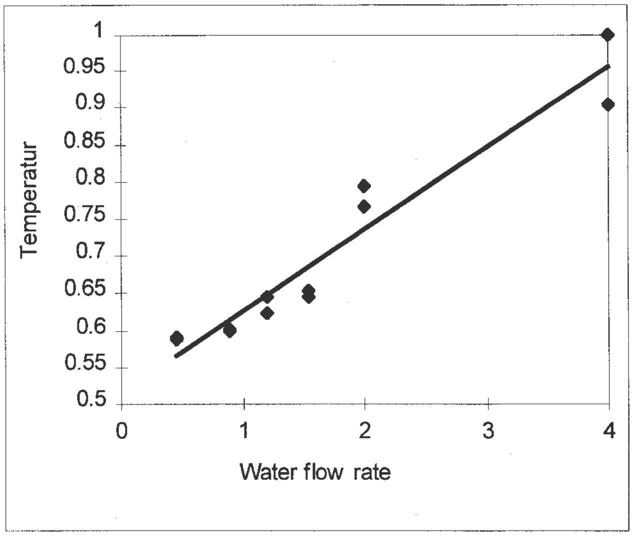

Figure 5: Effect of water flow rate on Leidenfrost temperature at the impingement point.

Figure 6 shows the impact of normalized water flow rate on the normalized heat transfer coefficient corresponding to the Leidenfrost temperature (H_L). The variation is non-linear at low flow rates and the sensitivity to the flow rate is high. At higher flow rates the sensitivity is not as significant. This correlation shows the importance of an adequate initial water flow rate at the start of the cast.

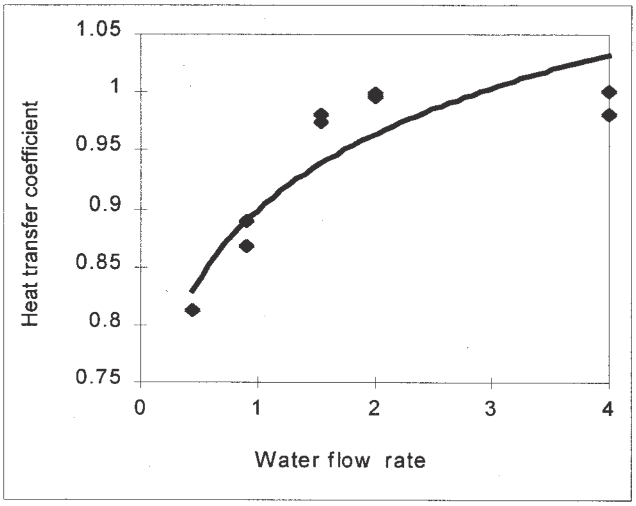

Figure 6: Effect of the water flow rate on Leidenfrost heat transfer coefficient at the impingement point.

The experimental set-up was also used to cool the test block with pulsed water technology [8]. The cycle time and the off percentage (percentage of the cycle time where the water flow rate was cut-off) were studied. A typical normalized heat transfer coefficient curve is shown in figure 7. The effect on the initial test block surface temperature between each cycle can be observed as also reported in [3]. This implies that each cooling cycle is independent and that heat transfer coefficients are intimately linked to the initial surface temperature.

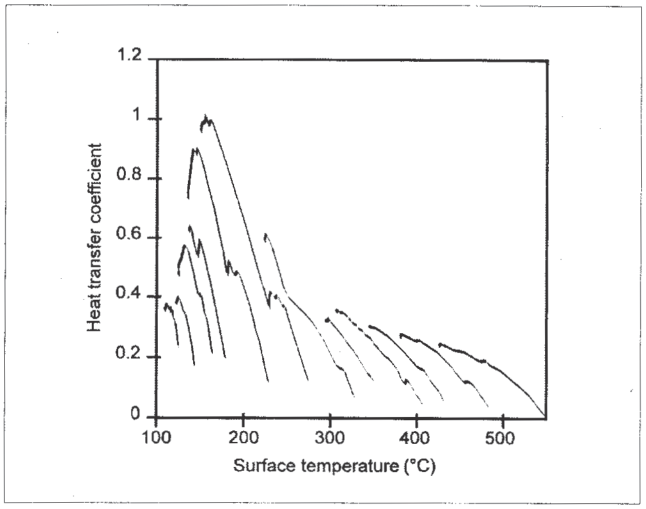

Figure 7: Effect of pulsation on heat transfer coefficient.

The impact of water temperature was also studied with the experimental rig. Figure 8 gives the effect of this variable on the Leidenfrost heat transfer coefficient (H_L). It can be seen that the significance of water temperature is small, between 5^{o}C and 20^{o}C. Beyond these values the heat transfer coefficient decreases rapidly as a function of water temperature, as reported elsewhere [9]. Even if the heat transfer coefficient does not vary at low temperatures, the final heat flux will change since it is related not only to the heat transfer coefficient but also to the water temperature. There is in fact a 5% difference between heat fluxes at 5°C and 25° C, but a much bigger reduction (40%) from 25°C to 50°C.

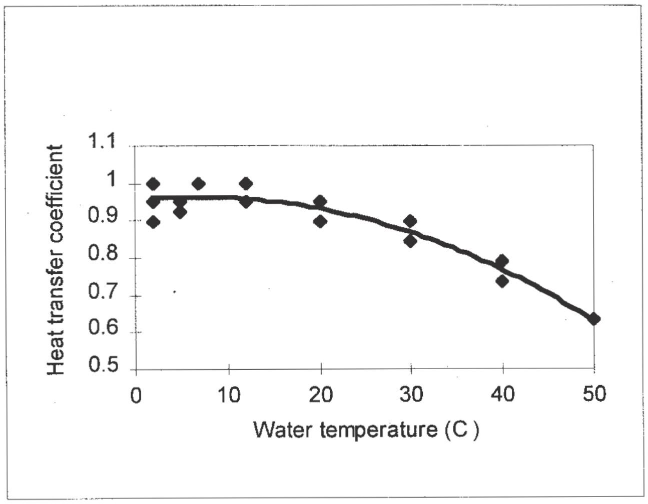

Figure 8: Effect of water temperature on Leidenfrost heat transfer temperature coefficient.

Influence of Casting Parameters on Ingot Behavior at the Cast Start-up

Important relationships can be established between the heat transfer coefficients and the casting parameters, but the main objective is ultimately to gain understanding and control of the start-up behavior in relation to the casting parameters used, mould type, ingot size and alloy. The relationships established in the previous section were integrated into the Alcan DC casting transient model [10,11]. Parameters such as casting speed, water flow rate, pulsation cycle and off percentage, casting temperature and filling recipes were systematically studied with this mathematical model in order to determine their impact on the thermal behavior of the ingot butt at cast start-up. Over 80 simulations were performed with the casting model. Some of these simulations were compared with temperatures recorded by thermocouples immersed in the ingot butt at the start of the cast. Comparisons were good enough to apply the model for a wide range of cooling conditions. Some examples of the effect of usual casting parameters are presented below.

Figure 9 shows typical temperature fields inside the ingot during the film boiling regime and the nucleate and convective regimes. The sump formation and the reduction of surface temperature can be clearly seen in this figure.

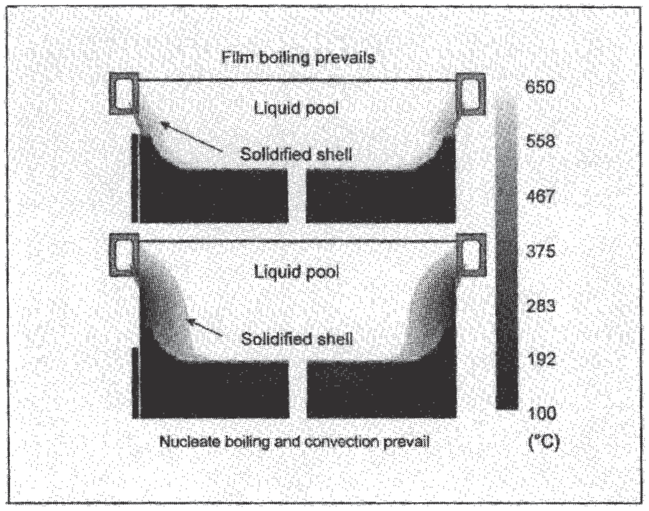

Figure 9: Typical temperature field inside the ingot at cast start-up.

The initial casting speed was varied from 20 mm/min to 50 mm/min. The 2-D finite volume, transient casting model was then applied to calculate the thermal profile of the ingot (600 mm x 1800 mm) cooled with pulsation technique. Figure 10 shows the resulting calculated internal ingot butt temperature coming from a "modeled immersed thermocouple". As can be seen in this figure, a lower casting speed results in a lower temperature, as the heat input is decreased.

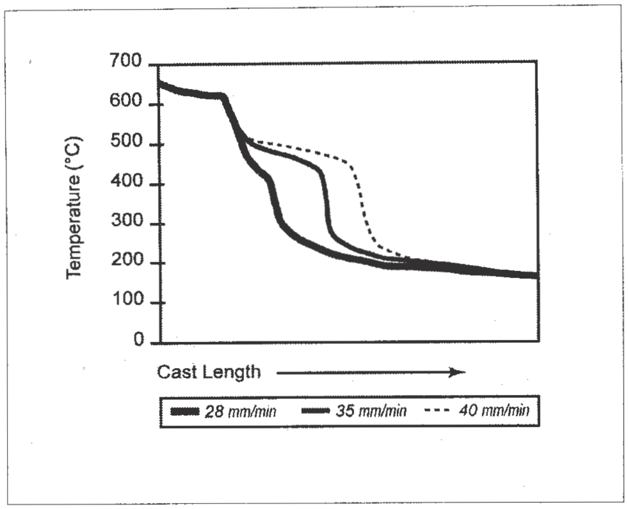

Figure 10: Internal ingot temperature as a function of casting speed.

Figures 11 and 12 respectively show the influence of the initial off percentage and initial water flow rate for the same ingot size for the same pseudo-thermocouple. It can be seen that these two parameters also have a significant effect on the thermal behavior of the ingot. Increasing the initial percentage off of the pulsation valve and decreasing the initial water flow rate cause an increase in internal temperature. These results show that the selection and adjustment of these parameters are crucial in order to maintain a desired temperature evolution that will lead to defect-free ingots. These three figures show the usefulness of such a model, coupled with good understanding of boundary conditions that can be used to give more flexibility and confidence in the selection of the numerous parameters involved in the cast start-up practices. Furthermore the relationship between the predicted temperature profile and the cast start-up performance will be established to define the best operating zones for each specific alloy and ingot size.

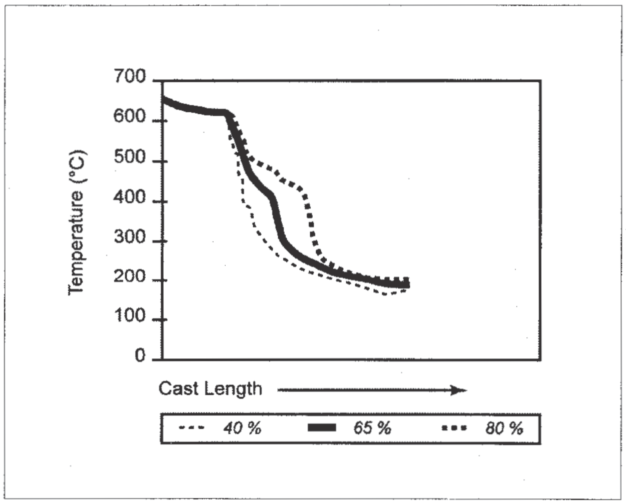

Figure 11: Internal ingot butt temperatures as a function of initial percentage off.

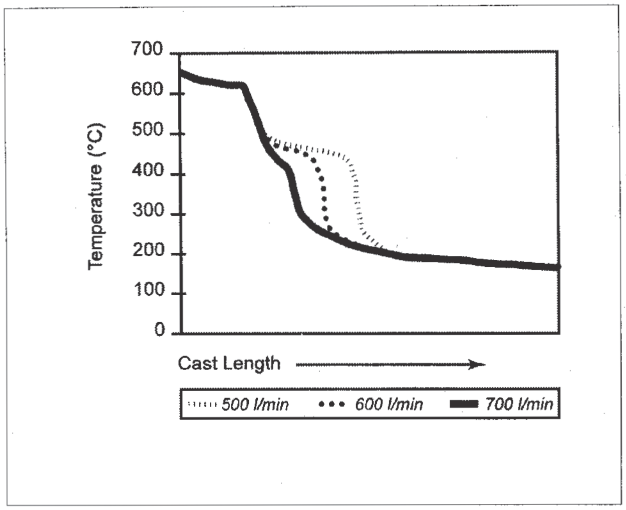

Figure 12: Internal ingot butt temperature as a function of initial flow rate.

Conclusion

This paper summarizes the results obtained with the experimental determination of heat transfer coefficients as a function of various casting parameters. The results were integrated into a transient DC casting mathematical model and the major casting parameters were systematically studied in order to quantify the sensitivity of the ingot butt response to their variation. This complete set of relationships will be applied to increase the understanding and control of the ingot butt thermal behavior during a cast start-up. This work along with plant performance evaluations will allow to progress in the quantification of the ingot butt thermal behavior which is intimately linked to the numerous process parameters.

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