Real-Time Control of Thermal Balance based on Ingot Surface Temperature Measurements in Aluminium DC Casting for Enhanced Ingot Quality

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Abstract

Direct Chill (DC) casting is a semi-continuous process that involves pouring molten aluminium into a water-cooled mould and a starting head that moves downward to progressively form the ingots. The start-up phase (transient) of DC casting is crucial for ensuring the quality of the ingots, as defects and cracks mostly occur during this period. The balance between the heat input from the molten metal and the cooling provided by the process water is critical. Despite well-defined casting parameters, process variations can destabilize the thermal balance and generate ingot defects. By measuring the ingot surface temperature, a few millimetres below the water impingement point near the centre of the rolling face, it is possible to continuously visualise the ingot thermal balance during the start-up phase. During start-up, various heat transfer regimes are observed, including film boiling, nucleate boiling, and convection that typically lead to the steady-state phase of the cast. Controlling these heat transfer regimes allows for better management of the ingot curl rate associated with major ingot defects.

The objective of this study was to establish the relationship between the ingot surface temperature profile and the likelihood of defects. Subsequently, a process control loop was developed to automatically adjust the casting water flow rate in real-time to achieve the optimum thermal profile. The development of the technology was carried out in three steps. Initially, tests were conducted at laboratory scale on a small ingot size with promising results. Second, tests were performed on a development platform with exceptionally controlled conditions during casting a single full-size ingot. The robustness of the control loop was validated by intentionally selecting a water flow rate outside the effective boundary to observe the capacity of the automated system to restore the optimal ingot thermal profile. The results were conclusive, and the industrial demonstration was conducted in a real production plant environment and full-size ingots.

It was demonstrated that the control loop system and response time were effective in maintaining the ideal ingot thermal profiles to achieve the targeted ingot curl rate regardless of process variations. The benefits are particularly significant for crack-prone alloys that typically have a narrower operational window.

Keywords: DC Casting, Ingot quality, Nucleate boiling, Real-time control, Crack-prone alloys.

1. Introduction

Direct Chill (DC) casting involves pouring molten metal into a water-cooled mould, where the metal solidifies into ingots. The thermal dynamics of the solidification process are governed by the heat brought in by the incoming liquid metal and the heat extracted by the cooling water. The initial phase of casting is crucial, as it determines the thermal balance and quality of the ingot [1]. One key manifestation of this thermal-mechanical interaction is the butt curl, a curvature at the bottom of the ingot that reflects the local solidification conditions. Excessive cooling can lead to high tensile stresses and an exaggerated butt curl, while insufficient cooling can result in a flat butt and hot cracks, both of which are undesirable. The quality of the ingot butt is critical not only for downstream stability but also for preventing cracks [2]. Despite advancements in DC casting technology, variations in process parameters often lead to inconsistencies in ingot quality. These fluctuations disrupt the thermal equilibrium of the casting process, making it difficult for traditional control methods to adapt, resulting in defects that compromise the structural integrity of the ingots [3]. Variations in water chemistry and temperature particularly contribute to these inconsistencies, leading to defects in the ingot butts [4–6]. The accurate quantification of the heat extraction capacity of the cooling water has been identified as a critical factor in maintaining thermal stability during the DC casting process [7]. Figure 1 shows a schematic view of DC casting.

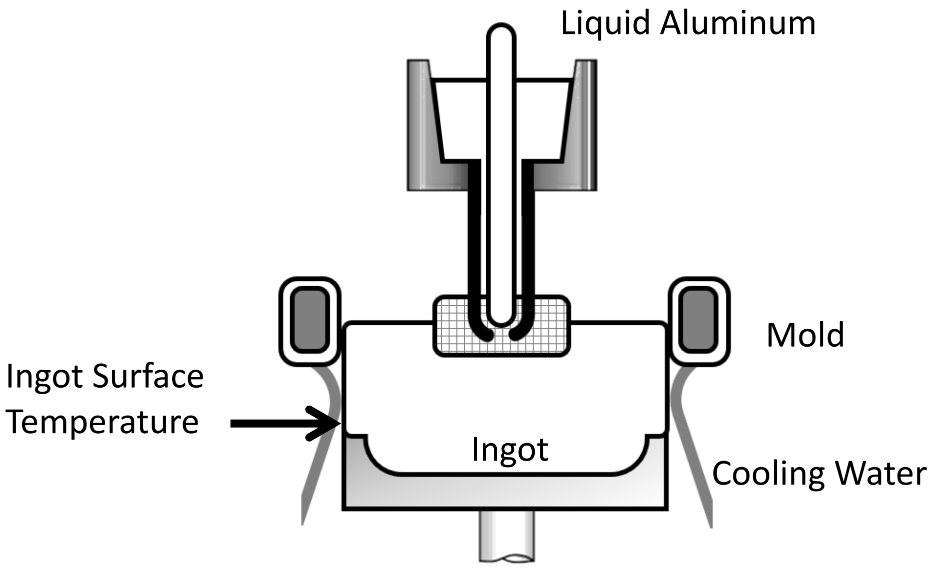


Figure 1. Schematic view of DC casting.

When cooling water comes into contact with the hot ingot surface, heat is transferred from the solid to the liquid through different boiling regimes depending on the surface temperature. Initially, at very high temperatures, a stable vapor layer forms between the solid and the liquid—this is known as film boiling, which acts as an insulating barrier and limits heat transfer. As the surface cools, nucleate boiling occurs, characterized by the formation of vapor bubbles at discrete nucleation sites on the surface, significantly enhancing the heat transfer rate. Eventually, the system reaches steady state, where the heat flux stabilizes and boiling ceases [8, 9]. Measuring the temperature profiles on the surface of the ingot a few mm below the point of impact of the cooling water allows observation of the different phases of heat transfer. These thermal profiles are directly linked to the onset of butt curl and the formation of defects at the ingot base, making them a valuable indicator of solidification quality and casting stability. Typically, thermocouples are inserted into the liquid metal, but this method is destructive and not applicable in an industrial context [10]. Therefore, in this study, the temperature was measured on the external surface of the ingot, allowing observation of the same heat transfer phenomena. Figure 2 illustrates the different boiling regimes and the corresponding heat transfer behaviour during the cooling of a hot surface in contact with water.

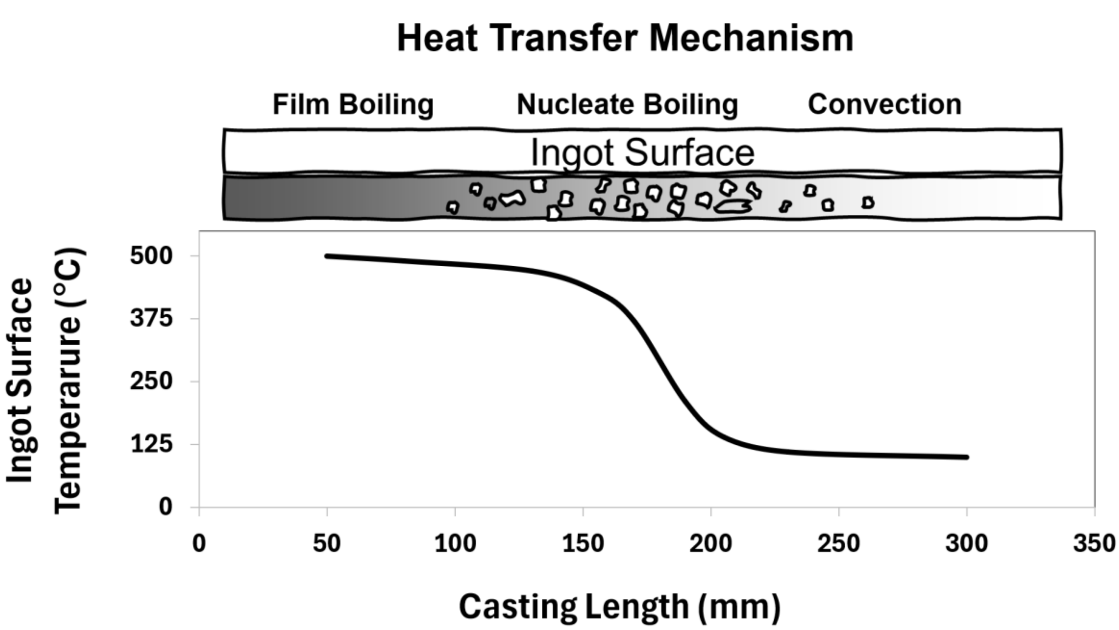


Figure 2. Schematic representation of boiling regimes: film boiling, nucleate boiling, and convection.

It is hypothesized that controlling the water flow rate with a control loop could manage heat transfer in real-time and achieve an ideal thermal profile to ensure ideal butt curl and perfect ingots with every cast. This approach could ensure optimal cooling rates and minimize defects such as cracks. The objective of this work is to develop a feedback control system that adjusts the water flow rate in real-time based on temperature readings, maintaining the ingot temperature within a predefined operational window. The challenge lies in developing a robust control system that is efficient under varying industrial conditions and can dynamically respond to real-time temperature measurements to adjust cooling rates accordingly. The concept of using temperature as a control input for process optimization was introduced as early as 1997, as described in [11], which outlines a method based on in situ temperature measurements to adjust process parameters in real time. Similar approaches have also been proposed in the literature, using the butt curl as the control element for process optimization [12, 13]. None of these strategies were validated under industrial operating conditions. Additionally, a patented method describes a cooling system in which the orientation of coolant jets is dynamically adjusted during casting to modulate the heat extraction rate and minimize cooling-related defects [14].

The methodology presented in this paper involves extensive experimental trials conducted at various industrial platforms, including lab-scale setups, industrial size demonstration platforms, and full-scale industrial sites. The findings from this research will contribute to the development of more efficient and reliable DC casting processes, ultimately enhancing the quality and consistency of sheet ingots. Additionally, improvements in process stability are expected to increase metal recovery, minimize remelting, and enable higher casting capacity, while also reducing potential safety hazards.

2. Methodology

The methodology for this study was structured into three distinct phases, each conducted at different scales and environments to ensure comprehensive evaluation and validation of the control system. In all cases, the surface temperature of the ingot was measured a few mm below the water impingement point, at the centre of the rolling face. An instrument was developed to measure the surface temperature of the metal at the start of the cooling process to observe the evolution of heat exchange. The instrument consists of a thermocouple using two dissimilar conductors. The electrical junction is made by the aluminium from the ingot. This type of installation allows direct measurement of the material's temperature, avoiding problems of inadequate contacts. This device is installed directly under the mould, where the liquid metal has just solidified. The temperature measurement of the ingot begins at approximately 60 mm of casting length, the distance required for the ingot surface to descend sufficiently after the start and align with the measurement system. Additional information regarding the measurement methodology is available in patent from Auger and Caron [15].

In direct chill casting of rolling ingots, improper thermal conditions at the start of the cast can lead to significant explosion risks. If the conditions are too cold, excessive ingot camber can cause leaking and trap water between the stool cap and the metal, leading to violent steam explosions. Conversely, overly hot conditions can delay solidification and allow molten metal to breach containment, increasing the risk of contact with water, potentially causing explosions or metal run-out incidents [16]. This risk was taken very seriously during the various phases of development, and specific measures were implemented to ensure safety. One key element was limiting the maximum percentage correction requested by the control system. This approach prevents excessively large or aberrant corrections due to measurement errors or programming issues. The correction limit could be adjusted according to the test conditions and the maturity of the system.

2.1 Phase 1: Lab Scale Development

The initial phase involved lab-scale experiments. The primary objective was to develop and test the control algorithms in a controlled environment. A series of experiments were conducted using a lab-scale casting unit with a water mould size of 200 × 600 mm. Various alloys, including AA1050, AA3104, AA5052, AA5182, and AA6111, were tested to evaluate the performance of the control system under different conditions. The experiments focused on measuring the surface temperature of the ingot and adjusting the water flow rate in real-time to maintain the temperature within the optimal range. Over 200 casting trials were performed, allowing for the development and refinement of the control algorithms. These development trials are not presented here; instead, the focus is on evaluating the capability of the system.

Final trials were conducted to test the performance of the control system. The alloy AA6111 was chosen. All castings were completed with the same speed and metal level parameters. Initially, three castings were performed without using the control system: one cold, one centred, and one hot. The goal was to obtain three temperature profiles representing the normal process variations observed in industrial settings. The water flow rate parameters were varied by approximately 20 % to reproduce process variations. Subsequently, the cold and hot recipes were repeated using the control system to adjust the water flow rate based on real-time temperature measurements.

2.2 Phase 2: Industrial Size Demonstration

The second phase involved scaling up the experiments to an industrial size demonstration. This phase aimed to test the control system in a more realistic production environment. For these trials, the casting pit was configured to accommodate a single ingot, allowing for focused assessment of system performance under simplified industrial conditions. The mould used was a Wagstaff Epsilon™ 711 × 1638 mm, and the alloy tested was AA5182. The primary goals were to determine the ideal temperature target and evaluate the performance of the control system under significant process variations. The trials included reducing the water flow rate by 20 % and allowing control adjustment to assess the system's ability to maintain the target temperature. For safety reasons as explain previously, cold conditions were not tested.

2.3 Phase 3: Full-Scale Industrial Trials

The final phase involved full-scale industrial trials at one Rio Tinto site. This phase aimed to validate the control system's performance in a real production environment. The casting pit was configured to accommodate five ingots, reflecting standard industrial practice. However, temperature measurements were acquired from only two of these ingots to monitor thermal behaviour across the casting line. The control strategy, nonetheless, was based solely on the readings from a single instrumented ingot, under the assumption that inter-ingot thermal variation remained within acceptable limits. The second instrumented ingot served as a learning reference, enabling post-trial analysis of spatial temperature consistency and control robustness. The trials were conducted using an instrumented mould with temperature measurement systems and new control algorithms programmed into the automation systems. The trials focused on ensuring the safety, reliability and efficiency of the algorithms during the initial stages of casting, where defects are most likely to form. The objective was to validate whether the control system can dynamically respond to real-time temperature measurements and adjust cooling rates accordingly, maintaining the ingot temperature within the optimal range and improving the overall quality of the ingots. For safety considerations, the original water flow rate and casting recipe were kept unchanged in the industrial context. Only the performance of the control strategy was evaluated within the bounds of normal process variability, under strictly enforced operational limits to avoid any significant deviation from standard practice.

3. Results and Discussion

3.1 Phase 1: Lab Scale Development

Figure 3 illustrates the process parameters for three casting conditions: cold, centred, and hot. All three castings utilized the same alloy, AA6111, and identical casting parameters, except for the water flow rate. The left side of the figure shows the measured water flow rates, while the right side presents the ingot surface temperature profiles. The cooling water flow rates were adjusted by approximately 20 % to simulate typical process variations. As expected, the extent of the nucleate boiling region varied significantly with the applied flow rate, measuring 115 mm, 170 mm, and 235 mm for the cold, centred, and hot recipes, respectively. These thermal profiles are representative of normal industrial process variability and may be associated with cold shut defects or hot cracking in the ingots.

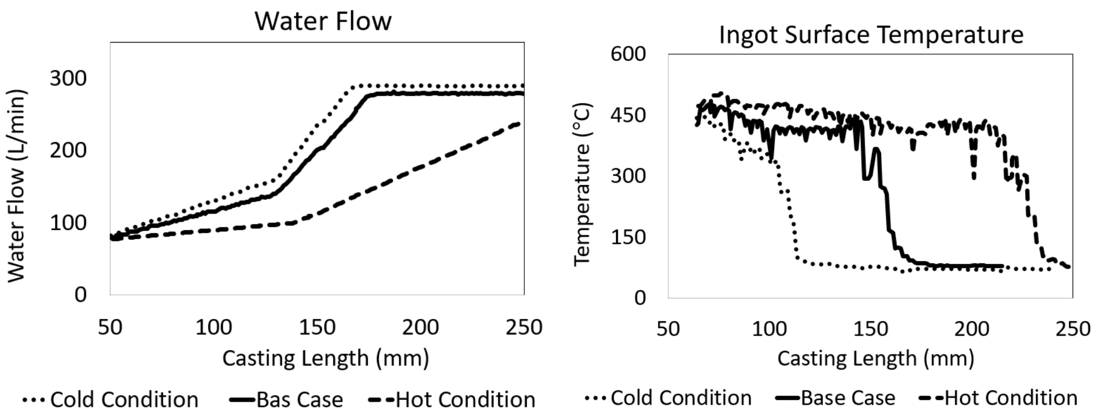


Figure 3. Process parameters for three casting conditions.
Left: water flow measurements, Right: ingot surface temperature.

The initial step involves defining the optimal thermal profile, which will serve as the reference for the control system. Ensuring the visual quality of the ingot butt is crucial, as it guarantees a high-quality ingot. The thermal profile measured for this ingot is then utilized to establish the control target. This target is derived through a straightforward linear modelling of the ideal thermal profile. The left side of Figure 4 displays a photograph of the ingot exhibiting excellent quality, while the right side illustrates the measured temperature curve alongside the corresponding target.

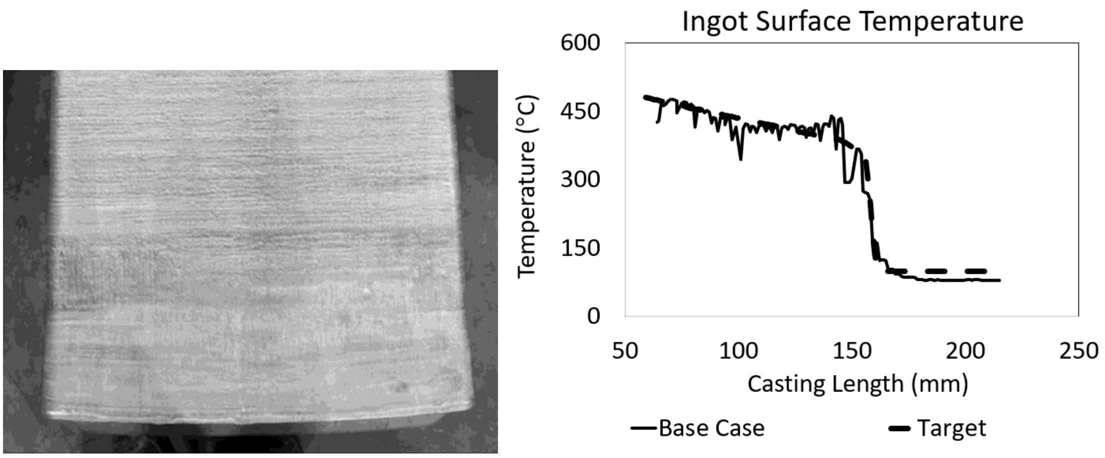
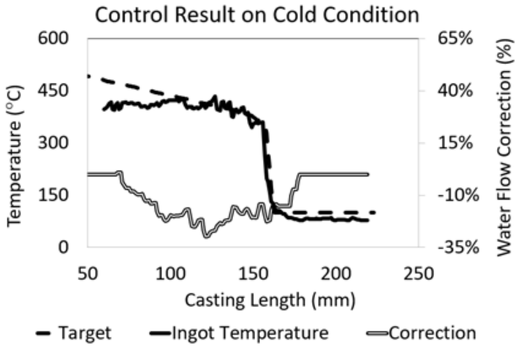


Figure 4. Establishing target casting temperature from ingot butt quality assessment for lab scale trials. Left: Picture of ingot butt. Right: Definition of optimal surface temperature based on ingot measurements.

The cold recipe was subsequently repeated, utilizing the control loop to adjust the water flow rate based on real-time ingot temperature measurements. The results are depicted on the left side of Figure 5, which illustrates the percentage correction applied to the water flow rate by the control system and the corresponding temperature curve. This graph also displays the target temperature used for the control. The end of the nucleate boiling phase shifted from 115 mm (see Figure 3) to 170 mm. The average correction required for the water flow rate was -17 %, with a maximum correction reaching -25 %. The graph shows that the initial ingot temperature was colder than the target, and the impact of the reduced water flow rate on the temperature brought the ingot temperature back to the target at around 110 mm of casting. The control loop significantly corrected the ingot temperature curve, achieving a profile that aligns with the target.

The hot recipe was subsequently repeated, using the same strategy to adjust the water flow rate based on real-time ingot temperature measurements. The results are depicted on the right side of Figure 5, which illustrates the ingot temperature and the percentage correction applied to the water flow rate. The black curve represents the ingot temperature, while the dashed black curve indicates the target temperature. The double-line curve shows the correction applied to the water flow rate. The end of the nucleate boiling phase shifted from 235 mm (see Figure 3) to 178 mm. The average correction required for the water flow rate was +29 %, with a maximum correction reaching + 50%. The ingot temperature was slightly above the target at the beginning of the casting, prompting the control system to gradually increase the percentage correction. The effectiveness of the control is particularly evident between 125 and 175 mm of casting, where the vapor film was eliminated despite the tendency of the temperature to exceed the target. The control loop also proved effective in regulating the water flow rate under hot conditions.



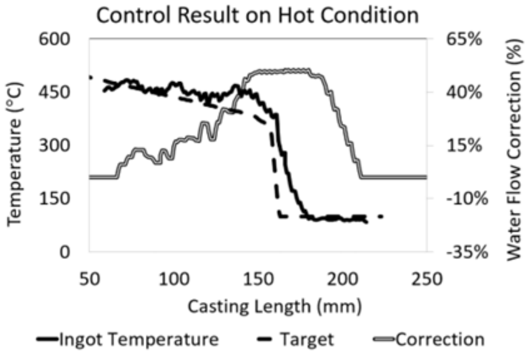


Figure 5. Temperature control results: measured vs target and corrections applied. Left: Cold conditions. Right: Hot conditions.

3.2 Phase 2: Industrial Size Demonstration

The same approach was subsequently employed to test the control system on an industrial-scale ingot using a one ingot casting pit. AA5182 alloy was tested, utilizing a Wagstaff Epsilon™ technology mould with dimensions of 711 × 1638 mm. Initially, a baseline casting was performed without control to define the target temperature profile and confirm the target with the visual aspect of the ingot foot. Figure 6 presents, on the left, a photograph of the ingot and, on the right, the results of the casting. The graph displays the water flow rate used, the ingot temperature, and the defined target. Although the ingot exhibited a relatively significant oxidation band in the transition zone, it was free of cracks or defects. The casting parameters could be improved to reduce the oxidation zone, but this was beyond the scope of the trials.

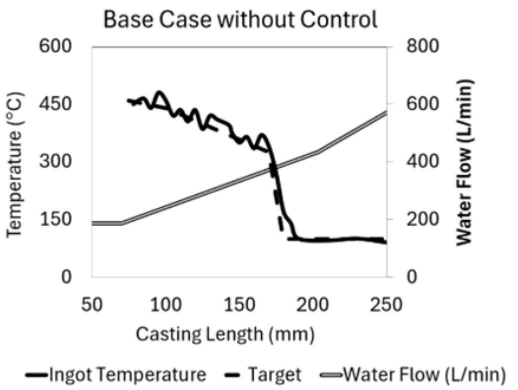


Figure 6. Establishing target casting temperature from ingot butt quality assessment for industrial scale trials. Left: Picture of ingot butt. Right: Definition of optimal surface temperature based on ingot measurements.

To evaluate the performance of the control loop, the water flow rate was reduced by 20 % compared to the baseline casting. Figure 7 presents a photograph of the cast ingot in these conditions and the results of the trial. The graph illustrates the relationship between the ingot temperature, the target temperature, and the correction applied during the casting process under hot conditions with control. As expected, the ingot temperature was initially higher than the target at the beginning of the casting. The temperature gradually approached the target as the control system increased the water flow rate. Between 125 and 200 mm, the percentage of corrections oscillated near the maximum permissible value of +25 %. The vapor film was eliminated around 190 mm, which is acceptable and relatively close to the target. This test confirmed that the development of the system in the laboratory was replicable on a full-scale format, demonstrating a sufficiently robust system for future trials in an industrial production environment.

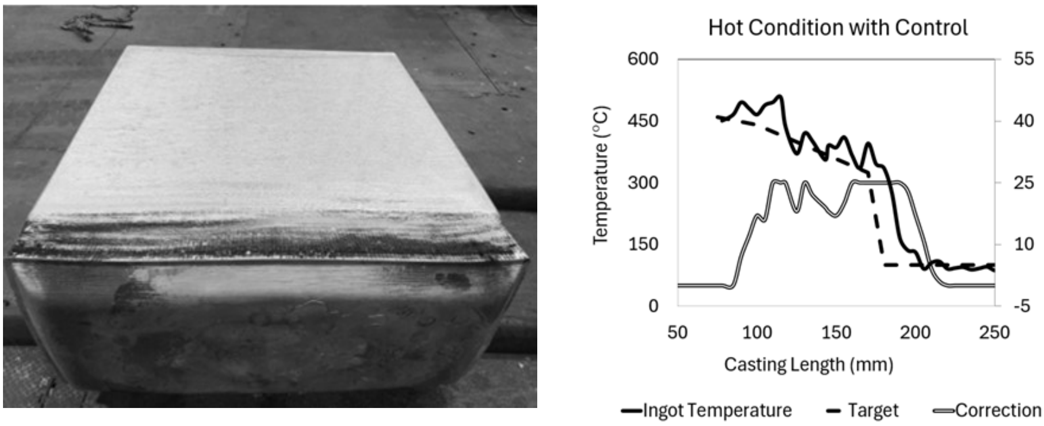


Figure 7. Trial outcome under hot casting conditions. Left: Picture of ingot butt. Right: Temperature control results: measured vs target and corrections applied.

3.3 Phase 3: Full-Scale Industrial Trials

The final phase involved testing the control system in an industrial environment. The trials were conducted at a Rio Tinto site, using a vertical casting pit with five ingots. All tests were performed on 6xxx series alloys, utilizing Wagstaff Epsilon™ technology moulds with dimensions of 660 × 1880 mm. For the safety reasons previously discussed, the maximum control adjustment was limited to ±10 %. The original water flow rate used in the casting practice was maintained unchanged, and stringent control limits were established to prevent any significant deviation from the established process conditions. Figure 8 illustrates the results of four full-scale industrial trials. Each graph of Figure 8 presents the ingot temperature, the target temperature, and the percentage correction as a function of the casting length. These graphs demonstrate the behaviour of actual ingot temperatures relative to the target temperatures and the corrections applied during the industrial casting process. Based on the measured temperature, the system adapts the correction to bring the temperature back to the target. The various trials allowed testing under both hot and cold conditions, with significant adjustments to the water flow rate. All ingots from these castings were free of cracks and exhibited butts with adequate visual quality. The effectiveness of the control system is evident in its ability to maintain the ingot temperature within the desired range. The system's response time proved adequate to exert a timely and meaningful influence on the ingot during the critical early stages of casting. The control system's adjustments ensure that the ingot temperature aligns closely with the target, minimizing the risk of defects and ensuring high-quality ingots.

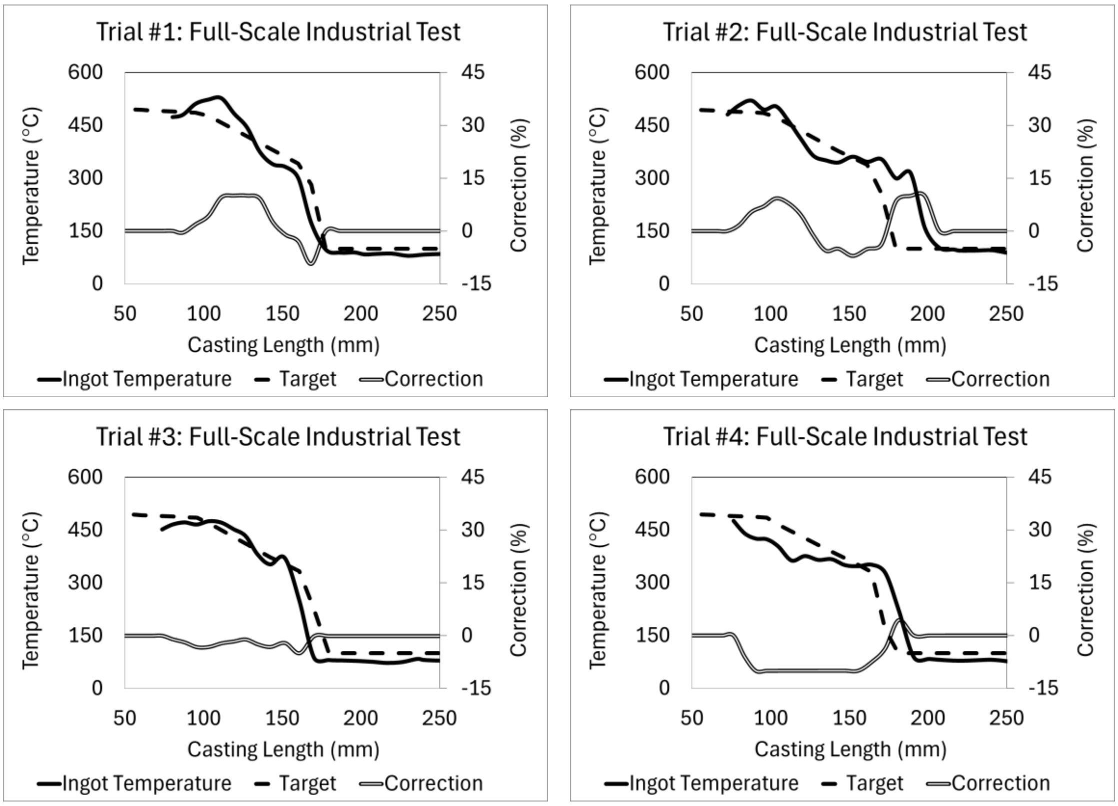


Figure 8. Example results from on-site industrial testing under hot conditions.

4. Conclusions

The development and implementation of a real-time control system for managing the thermal balance during the start-up phase of aluminium DC casting have demonstrated significant improvements in ingot quality. By continuously measuring the ingot surface temperature and adjusting the cooling water flow rate through a control loop, the system effectively maintains the optimal thermal profile, minimizing defects such as cracks and butt curl.

The study's phased approach, from lab-scale experiments to full-scale industrial trials, validated the robustness and efficiency of the control system under varying conditions. The results indicate that the control system can dynamically respond to real-time temperature measurements, ensuring consistent ingot quality across different alloys and casting environments. This advancement is particularly beneficial for crack-prone alloys, offering a narrower operational window and enhancing the overall reliability of the DC casting process.

The successful integration of this technology into industrial settings could marks a significant step forward in the field of aluminium casting, promising enhanced productivity, reduced defect rates, and improved ingot quality. Future work may focus on developing an ingot temperature measurement system with more industrial and operational ability by production sites.

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