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

Josée Colbert[1], Joseph Langlais[2], Éric Laplante[3], Dominique Lavoie[4] and Annie Martel[5]
1. Casting specialist and data science 4.0
2. Director Integrated Productivity, Casting & Products
3. Instrumentation program manager
4. Metallurgical Technician
Rio Tinto, Saguenay, Canada
5. Process Control Developer
Génitique, Saguenay, Canada
Corresponding author: josee.colbert@riotinto.com
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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.

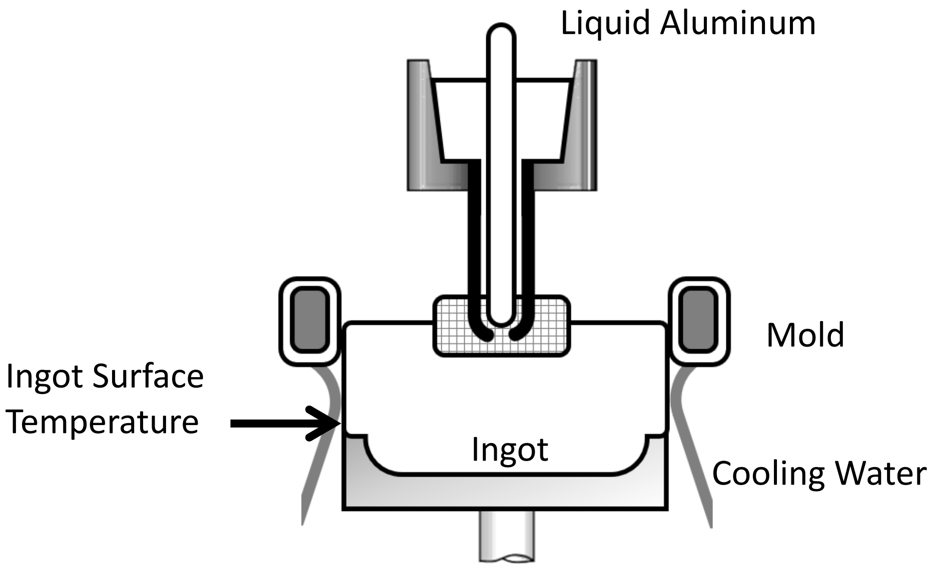

Figure 1. Schematic view of DC casting.

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.

6. References

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