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Computational model for multi alloy casting of aluminum rolling ingots

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ABSTRACT

Direct Chill (DC) casting is the primary route to produce rolling ingots in an industrial setup. During DC casting, the temperature field, fluid flow and solidification profile strongly depends on the ingot cooling practice. Further, the temperature field affects the macro/micro structure and defects which in turn determine the quality of the ingots produced. The present work focuses on the development of a steady-state computational fluid dynamics (CFD) model which appropriately treats heat transfer, fluid flow and solidification during multi alloy DC casting. This model is rigorously validated with experimental data from laboratory tests reported elsewhere. In multi-alloy co-casting, the simulation study is done to understand the effect of the casting speed and the metal distribution system. The present model is useful in providing an insight into the thermal-fluid flow and solidification profile that can help in identifying optimum process parameters.

Introduction

The Direct Chill (DC) casting process is a semi-continuous process for producing solid aluminum alloy rolling ingots from liquid melt. The processing conditions in the caster during phase change from liquid to solid have an influence on the microstructure and defect formation in the cast ingots which in turn affect the productivity. From the productivity and quality point of view, it is important to understand the interplay between the processing condition on defect formation which otherwise is difficult to gauge intuitively.

In the DC casting process, liquid melt is initially cooled in a shallow bottomless water-cooled mold made from aluminium whose cavity shape is based on the desired cross-section of the ingot. Initially an aluminium bottom block seals the mold cavity from the lower side. The sequence of the casting process is as follows: (a) the liquid melt is poured from the upper side into the water cooled mold (primary cooling). (b) the bottom block is lowered into a curtain of cooling water which further cools the metal in the periphery resulting in a solidified shell that holds the liquid sump as shown in Fig. 1. (c) the downward motion of the bottom block follows a specified casting speed profile. After the initial ramp-up of the casting speed, the casting progresses in steady state during which the thermal and solidification profiles do not vary with time.

In steady state casting, there are two distinct zones, namely primary and secondary cooling regions. The initial cooling at the periphery of the ingot is in the water cooled mold (known as the primary region) and cooling progresses at the periphery of the ingot with water directly impinging onto the surface (known as secondary cooling region). In the primary cooling region, heat extraction rate from the melt is very high because the melt is in direct contact with the water cooled mold. But, after the formation of this initially solidified shell an air gap is formed at the mold/ingot interface due to solidification shrinkage. This leads to a drop in the heat transfer within the mold region where air gap is present. Partial remelting of the solidified shell may result in due to this drop in the heat transfer rate. After the solidified ingot emerges out from the mold it goes into a secondary cooling region where it is further cooled by direct water impingement on the periphery of the ingot. In the secondary cooling region, cooling of the ingot is due to boiling heat transfer as the cooling water is in direct contact with the hot ingot surface. Based on the cooling conditions, the ingot surface temperature may vary between the solidus temperature of the metal and the ambient temperature. The changes in the cooling conditions during casting impact the microstructural features such as the dendritic arm spacing (DAS), grain size/distribution and the intermetallic particle size. The changes in solidification rate can influence intermetallic constituents formed. The type of the intermetallic formed during solidification is dependent on the alloy

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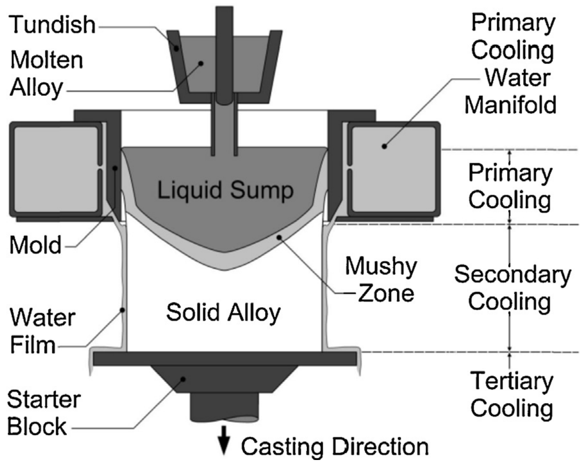

Fig. 1. DC casting setup and different components [reproduced from Baserinia et al. [9]].

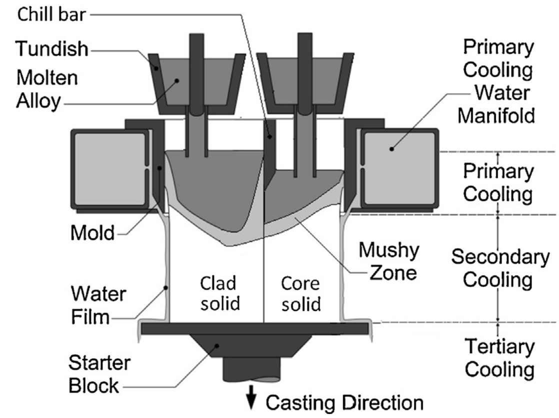

Fig. 2. Schematic of DC co-casting for multi alloy system.

composition and the local solidification rate. In the primary cooling region, slower cooling rate due to the formation of the air gap leads to the formation of a coarse grained shell. This region might have to be scalped for further processing leading to a decrease in the productivity. Considering the importance of the temperature and the solidification profile on the microstructure of the cast ingot during DC casting, it is desirable to develop a computational model which can provide insight into the casting process.

Several research works in the past articulate the utility of a mathematical model for understanding the DC casting process. Weckman and Niessen [1] simulated for steady-state thermal condition of DC casting of a cylindrical ingot, using the finite element technic. They developed a method to calculate the boundary conditions in the secondary cooling region using the theories of nucleate boiling with forced convection and film cooling. Their results are in excellent agreement with experimental data. Das [2] developed a steady state DC casting model using a non-orthogonal control volume discretization and coordinate transformation technic in a multi-domain framework, and validated his model with experimental data from Weckman and Niessen [1]. Fjær et al. [3] developed a thermal- fluid flow model and further coupled it with a stress model. They showed that the evolution of butt curl is dependent on the water incursion criterion which is closely related to the level of film boiling. Droste et al. [4] developed a thermo-mechanical model for DC-cast of aluminum ingots during the start-up phase. Grealy et al. [5,6] described the influence of the metal distribution system on heat transfer and the solidification behavior. The modeling tools provided insight into the understanding of the requirements and guidance for modification to arrive at a better metal distributor.

Using the commercial finite element code, ABAQUS, Sengupta et al. [7] developed a model to describe heat transfer during the start-up phase without considering the fluid flow. They have developed a comprehensive model for considering primary cooling, secondary cooling with water ejection and incursion at the interface between the bottom block and the ingot. A sensitivity analysis completed with the model has clearly identified the link between ingot base cooling and secondary water cooling heat transfer during the start-up phase. Willams et al. [8] developed a 3D comprehensive model for the start-up phase (transient) by coupling fluid flow, heat transfer, phase change, and thermal stress. The impact of the liquid flow distribution on the maximum stress value is more significant. Therefore, it may be possible to use the metal inflow distribution bag design to minimize the stress levels while respecting the thermal performance constraints required by the operators. Recently, Baserinia et al. [9] have proposed a simplified approach for the mold heat-transfer coefficient in the DC casting of a rectangular ingot which is a combination of a one dimensional air gap model with two dimensional CFD simulations for contact heat transfer coefficient (HTC) when the metal is in perfect contact with the mold. There has been considerable work reported in the literature on steady state modeling of the DC casting process but rigorous validation of the model for various casting speeds, alloy grades, temperature and sump profile for single and multi-alloy casting have not been reported.

Clad aluminium alloys (clad alloys) sheets have many commercial applications such as brazing sheets, Alclad series of aerospace alloys etc. Conventional cladding is accomplished by DC casting of the clad alloy and the core alloy separately. The clad alloy ingot is rolled to the required dimension and then welded to the core ingot. This composite ingot is then rolled to produce clad sheets. This technic forms a bottleneck in an industrial setting since the processes involved are unconventional (e.g., welding the clad and the core) and therefore are time consuming. To address this bottleneck, Anderson et al. [10] developed a technic for co-casting of multi-alloy, multi-layered, aluminum ingots (for Novelis Fusion^{TM}, see website: www.novelis.com/en-us/Pages/Fusion.aspx). A schematic of their DC co-casting process is shown in Fig. 2. This process allows co-casting of two or more alloys simultaneously which can then be rolled down into a clad sheet. It needs design of the mold and the cooling system based on cooling requirement of alloy combination.

As seen from reported literature [1–9] on modeling of DC casting process, the model provided insight into thermal and solidification profiles which was used for improvement of process. But, modeling of co-casting process has not been reported in literature. The equipment may need modification of design or processing condition for different alloy combinations because of the difference in the freezing temperature of the alloys. The multi-alloy co-casting setup needs thermal consideration of two alloys hence the process is more complicated as compared to single alloy casting. Therefore, for finding optimum design/process conditions during different alloy combination in a co-casting setup, a model of DC co-casting process can be a useful tool which provides insight into the thermal and solidification profiles.

The present work focuses on the development and validation of a steady-state computational fluid dynamics (CFD) model which appropriately treats heat transfer, fluid flow and solidification during multi alloy casting. The model validation has been done with temperature and sump profile measurements for multi-alloy co-casting [11].