CORPUS PUBLISHERS

Journal of Mineral and Material Science (JMMS)

Volume 1 Issue 4, 2020

Review Article

The Casting of AA6111 Aluminium Alloy Strips using Single and Double Impingement Types of Liquid Metal Feeding System

Niaz U, Isac MM, Guthrie RIL*

McGill Metals Processing Centre, McGill University ^{3610} University Street, Canada

Article Information

Received date : November 23, 2020

Published date: November 30, 2020

***Corresponding author**

R I L Guthrie, McGill Metals Processing Centre, McGill University 3610 University Street, Wong Bldg. Room 2M040, Montreal, Canada

Keywords

Horizontal Single Belt Casting Process (HSBC); Computational Fluid Dynamics (CFD); Double Impingement Feeding System; Single Impingement Feeding System

Abbreviations

HSBC: Horizontal Single Belt Casting Process; FVM: Finite Volume Method; SIMPLE: Semi-Implicit Method for Pressure Linked Equations

Abstract

In this research study, thin strips of AA6111 Aluminium Alloy were produced using the Horizontal Single Belt Casting (HSBC) process. Two different types of liquid metal delivery systems were investigated, namely "single" and "double" impingement, metal feeding systems. The double impingement feeding system possesses an inherent ability to reduce the final impact of the molten metal with the moving belt, reducing a considerable part of the molten metal's kinetic energy, by first impacting the inclined refractory plane. By contrast, the single impingement feeding system suffers no loss in its initial kinetic energy, before striking the moving belt. This can result in greater penetration of molten metal back into the quadruple region, possibly leading to the formation of skull, and possible termination of casting. The characterization of the strips produced, involves the microstructures analysis and three-dimensional surface roughness

1. Introduction

Horizontal Single Belt Casting process is a commercially proven method, and considered the most economical, for producing high-quality strips. The as-cast dimensions chosen, are closer to final desired sheet specifications, therefore requiring fewer hot reduction passes, as downstream processes [1]. This not only brings down the overall energy requirements of the sheet metal manufacturing process, but allows caster dimensions and most noticeably, the sizes of hot/cold rolling mills is drastically reduced. These attributes render HSBC, to be a more versatile, energy-efficient, easy to install, and relatively inexpensive, casting machine. Also, the HSBC process provides solutions to increasingly stringent environmental regulations imposed by regulatory bodies. These are impossible to achieve with conventional Continuous Casting (CC)/Direct Chill Casting (DSC) of ferrous/non-ferrous slabs, owing to the high energy demands required for these processes [1-7]. The present version of the HSBC caster, installed at MetSim Inc, involves feeding the molten metal at a preselected flow rate onto a chilled, moving belt, on which it solidifies to form a 3mm - 15mm thick strip. This process is equivalent to the Pilkington float glass technology, in which the molten glass is continuously poured over a bath of molten tin. There, it solidifies into a continuous glass sheet. After the strip is produced, the inline reductions using a pinch roll, mini mill are performed to produce the desired thickness sheet material [1-7]. Further, HSBC strip does not require any subsequent surface scalping treatment, after the casting process has finished. This is due to the homogenous distribution of alloying elements throughout the strip thickness, mainly due to the high cooling rates of molten metal during the solidification. By contrast, surface scalping is required in aluminum DC cast products, owing to inverse segregation of alloying elements along the surfaces. This is the result of molten metal with higher concentrations of alloying elements, being sucked back into the inter-dendritic channels, during the solidification process. As the segregation at the cast surface/subsurface would affect subsequent post-processing of the cast material, it must first be removed. This results in a yield loss, and extra capital investment [3-7].

1.1. The Scope of the Present Research

The success of the HSBC process rests heavily on the mechanisms through which molten metal is delivered on to a cooling substrate. Two different kinds of feeding systems were tested, generally classified into two major groups, i.e. single impingement, and double impingement, depending on how many times the falling stream of molten metal, encounters obstacles. The prime objective of this research study was to understand the dynamics of the molten metal flow in both systems. For this purpose, numerical models were formulated using Ansys Fluent software whereas the experiments were performed using the pilot HSBC system [8,9]. The microstructure and surface roughness of the strips were evaluated and compared. As expected, and observed, the strip microstructure and surface quality were independent of the two feeding systems. AA6111 was selected for the casting experiments, being light in weight, and possessing fair strength and ductility. It is therefore used in the fabrication of body-in-white (BIW) automotive structures. The main mechanism behind AA6111's increased strength is precipitation hardening, along with solid solution and work strengthening.

1.2. The Feeding Systems Used to Carry out Casting Experiments & Parameters Studied

A double impingement feeding system uses a refractory plane, inclined at an angle of 45° and positioned right below the nozzle slot outlet, as shown in (Figure 1a). The molten metal dispensing from the nozzle slot outlet, first encounters this plane, eventually reaching the moving belt, where it solidifies as a thin strip. This in contrast to a single impingement feeding system shown in (Figure 1b), where the molten metal stream does not encounter any intermediate obstacle and therefore, remains uninterrupted. As a result, the final impact of the molten metal is more aggressive and abrupt, for single vs double impingement feeding system [9,10].

In this research study, the fundamental differences between these two different feeding systems and their abilities to produce high-quality strips are numerically and experimentally assessed. The operating parameters were selected, keeping in view the specification of our pilot caster which consists of a water-cooled endless steel belt. The metal head in the tundish for both types of feeding systems was kept constant at 10mm. This translates to the velocity of 1m/s at the nozzle slot outlet, using the relationship presented in equation 1. The belt's velocity was fixed at 0.4ms^{-1}, since at higher speeds (> 0.4 ms^{-1}), the molten metal would not have enough time to solidify, keeping in view the length of the belt i.e. 2.6 m only. Under these operating conditions, the

How to cite this article: Niaz U, Isac MM, Guthrie RIL (2020) The Casting of AA6111 Aluminium Alloy Strips using Single and Double Impingement Types of Liquid Metal Feeding System. J Miner Sci Materials 1: 1018

present research study unravelled the following physical phenomena: (a) the stability of the meniscus at a quadruple region (a) point where the molten metal- free stream, air, and moving substrate, all meet each other), (b) the dynamics of the molten metal flow after it interacts with the moving belt, (c) the non-uniformity in the flow of the molten metal over the moving belt, and its subsequent annihilation, (d) the velocities of the molten metal at varying distances over the moving belt, (e) to determine the physical/mechanical properties of the strip i.e. the microstructure and three-dimensional surface roughness.

$$V = Cd\sqrt{2gh} \quad (1)$$

where V is the velocity, h is the molten metal head inside the tundish, and Cd is the coefficient of discharge.

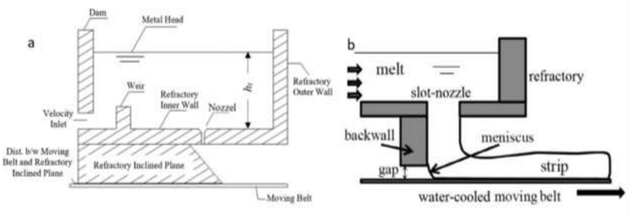

Figure 1: Different feeding system for the HSBC process, (a) Double impingement, (b) Single impingement.

1.3. Summary of Research Conducted to Date on HSBC Processing of AA6111 Aluminium Alloy

A considerable amount of research was conducted at McGill University in developing the HSBC process. Various delivery systems were tested, and molten metal flow behavior in each of them were examined. The most noteworthy work in that regard was the casting of high-quality AA6111 strip using single and double impingement feeding systems. COMSOL Multiphysics and ANSYS Fluent software were used to carry out the numerical modeling, whereas a pilot-scale caster and a casting simulator were employed for the experiments, in order to test the numerical predictions. The strips were produced in a thickness range of 2-8 mm, whereas the strip width lies in between 100-250 mm. Some of the useful outcomes of these studies revolve around the fluctuations at the molten metal/ air interface at the quadruple, or four phase region, where molten metal, air, moving belt, and the inclined refractory plane, all meet each other. Additionally, considerable R&D efforts were made previously by *Dr. Donghui Li et al*, to understand the cooling capability of the chilled substrate as a function of its surface roughness. Ab-initio predictions of interfacial heat fluxes were used for detailed numerical studies. It was determined that air entrapped within the crevices of the chilled substrate, can significantly reduce the heat flux and greatly affect the bottom surface quality of the cast strip. Since these crevices on the substrate are filled with air, which could instantaneously heat up, and expand, while encountering the hot molten metal. These localized thermal expansions can lead to the formation of dimples at the bottom surface of the strip. These projections/dimples limit heat transfer owing to the loss of contact between, copper substrate and the molten metal which results in an overall reduction in interfacial heat flux value [1-10].

1.4. Details of the Model Set-Up

In this research study, numerical modeling was carried out using Ansys Fluent 14.5 software which is based on the Finite Volume Method (FVM). A two-dimensional transient state, a turbulent model was produced. For tracking an interface, Volume of the Fluid (VOF) model was used. The velocity and pressure variables were coupled via the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) method. More details can be found in the literature [8]. To improve on the accuracy, the advection terms were discretized using a 2nd order upwind scheme over the entire simulation domain, whereas the diffusion term was approximated by the central differencing scheme. The default under relaxation factors are chosen for velocity and pressure which were 0.7, and 0.3 respectively. The governing equations were solved until the residual reached to 1x10−6. The simulation domains were discretized into tetrahedral elements to achieve the desired results and different numbers of grid points were tested until mesh independent results were achieved. Finally, 323161 tetrahedral elements (for double impingement feeding) and 982200 tetrahedral elements (for single impingement feeding) were found out to be appropriate but at the same time, less computationally intensive exercise for obtaining the desired result The molten metal was treated as a newtonian, incompressible fluid, and all the physical properties were assumed to be constant. The dimensions of the simulation domain chosen to carry out the numerical modeling are 0.230 m in length, and 0.020 m in height.

2. Results and Discussion

2.1. Molten Metal Flow Behaviour in a Single/Double Impingement Feeding Systems and the Velocity Contours/Profile over Moving Belt

As discussed before, molten metal flows in both single and double impingement feeding systems are fundamentally very different. To further illustrate this concept, the molten metal velocity contours were obtained as represented in (Figure 2). Additionally, velocity profiles were evaluated along the lines drawn at varying distances from the quadruple region, stretched through the thickness of the molten metal as shown in (Figures 3 & 4). For a double impingement feeding system, during an impact of the molten metal with an inclined refractory plane, a significant part of the molten metal kinetic energy is converted to static pressure thereby slowing down the speed of the molten metal over the moving belt. The molten metal continues streaming over the inclined refractory plane, under the force of gravity. However, down the slope, the friction of the inclined refractory plane opposes its flow. As a result, the velocity of the molten metal before it impinges on to the moving belt is significantly lower than one would expect it to be under constant gravitational acceleration. The opposite is true for a single impingement feeding system, wherein, the velocity of the molten metal over the moving belt is relatively high as opposed to double impingement feeding. The peak velocity of the molten metal, obtained at 220mm from the quadruple region for a double impingement feeding system is approximately 1.1 m/s. At a similar distance of 220mm, the peak velocity determined for a single impingement feeding system is 1.25 m/s. This validates the idea presented here that double impingement feeding system has an inherent ability to reduce the velocity of the molten metal over the moving belt.

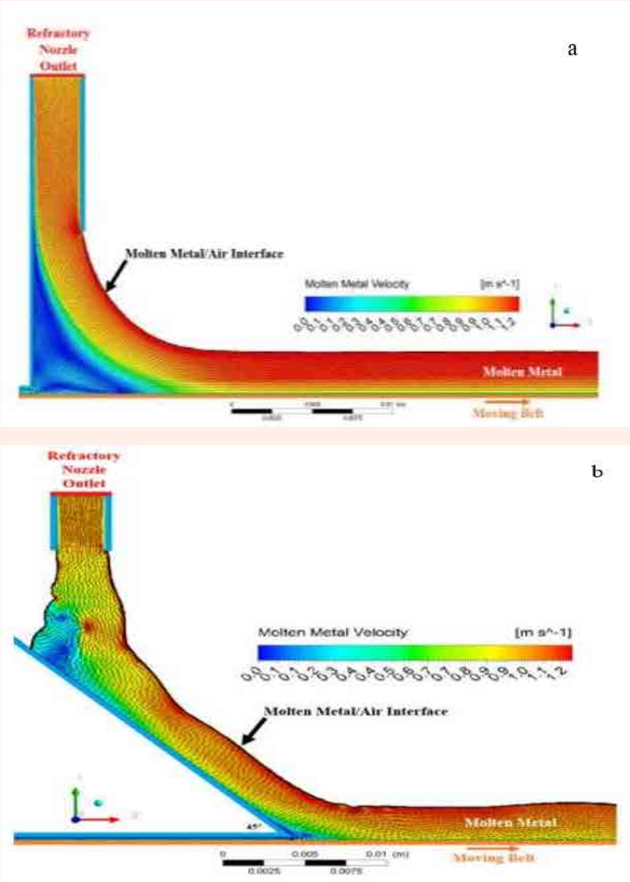

Figure 2: The simulated flow of the molten AA6111 in (a) Single impingement feeding system, (b) Double impingement feeding system.

Citation: Niaz U, Isac MM, Guthrie RIL (2020) The Casting of AA6111 Aluminium Alloy Strips using Single and Double Impingement Types of Liquid Metal Feeding System. J Miner Sci Materials 1: 1018

from low to high velocity, featuring a typical turbulent flow [11]. The flow is observed to be non-uniform during the first 60 mm of the moving belt for both feeding systems as shown in (Figures 3 & 4). However, by the end of the moving belt, the molten metal fluctuations seemed to be dying off. The experimental findings are in accord with the computational modeling results where the surface of the produced strips was almost flat and free from surface defects such as pinholes, blowholes, etc.

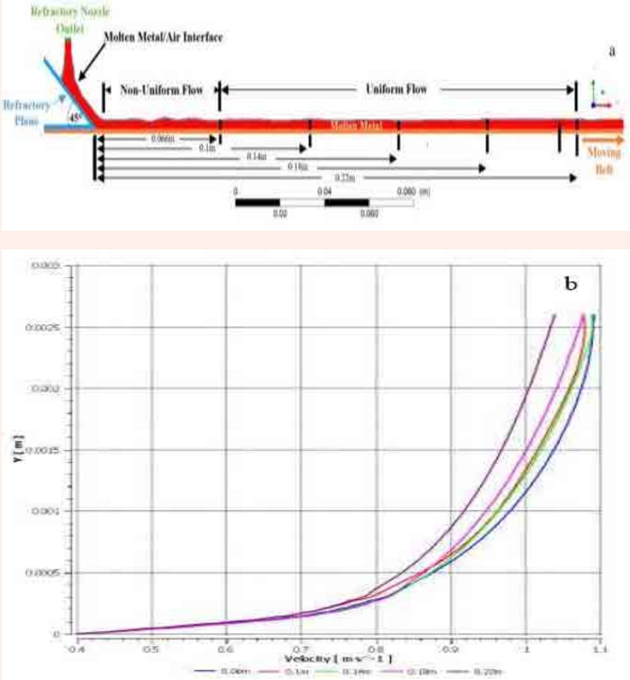

Figure 3: (a) Simulated flow of the molten AA6111 in the double impingement feeding system, (b) The velocity profile along these lines.

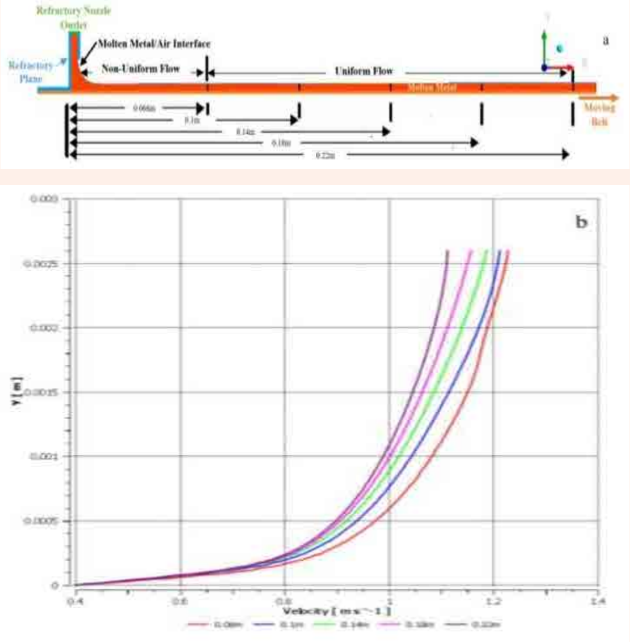

Figure 4: (a) Simulated flow of the molten AA6111 in the single impingement feeding system, (b) The velocity profile along these lines.

Near the Quadruple Region

The surface as well as the bulk quality of AA6111 aluminum alloy strip, produced through an HSBC process, depends on how effectively the flow of the molten metal at the quadruple region can be reduced or ideally stopped in order to avoid the formation of skull which may lead to curtailing the casting process [12]. This is achieved through minimizing the distance between the refractory block, (in case of a single impingement feeding system), and refractory inclined plane, (for a double impingement feeding system) with the moving belt as shown in (Figure 1a & 1b). In the present casting experiments, this distance was kept constant at 0.3 mm for both single and double impingement feeding systems.

Furthermore, the numerical modeling results show that, for both types of the feeding systems, under the specified operating conditions, the meniscus of the molten metal at the quadruple region remains highly stable and non-fluctuating. This is in accord with the experimental findings where a stable and non-penetrating meniscus has been observed. However, for a single impingement feeding system, a slight penetration of molten metal at the quadruple region is predicted as shown in (Figure 5a). This could be attributed to the fact that during an impingement of the molten metal with the moving belt, it tends to flow backward and could have solidified in there. However, under the present circumstances, the strong recirculatory flow in the immediate vicinity of the four-phase region, as shown in (Figure 5a), helped in keeping the metal in liquid state, by replenishing heat energy being lost to the belt, thereby preventing the formation of a frozen "skull", leading to a termination in casting, as discussed above. On the other hand, for the double impingement feeding system, the recirculation zone, adjacent to the quadruple region is not very strong as shown in (Figure 5b), however the penetration of molten metal into the four-phase region is also not observed, according to the numerical modeling predictions.

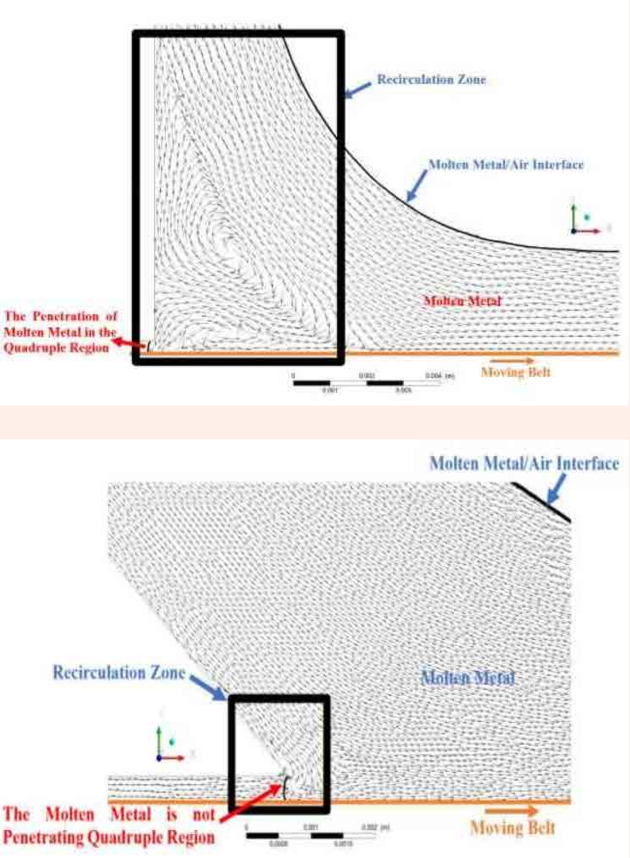

Figure 5: Circulating flow of the molten metal, adjacent to the quadruple region in (a) Single impingement feeding system, (b) Double impingement feeding system.

Citation: Niaz U, Isac MM, Guthrie RIL (2020) The Casting of AA6111 Aluminium Alloy Strips using Single and Double Impingement Types of Liquid Metal Feeding System. J Miner Sci Materials 1: 1018

A microstructural study was carried out using a Leica DM IRM optical microscope (Leica Microsystems, Concord, Ontario, Canada) to determine the grain size of the as-cast strip. The samples were prepared through using the conventional sample preparation technique i.e. starting with the coarser grid grinding process and eventually reaching to a finer one i.e. 1200 grid. The samples were than electropolished and etched using 2% Perchloric acid ($HClO_4$) in alcohol. The microstructure is characterized by very small grains, uniformly distributed across the entire thickness of the strip as shown in (Figure 6). The average grain size of the strip was found to be ~70μm, for single and double impingement feeding systems. The microstructure also shows porosities at various locations within the cast strip, very similar to DC cast product. The surface quality of the cast strip was observed to be satisfactory as shown in (Figures 7 & 8).

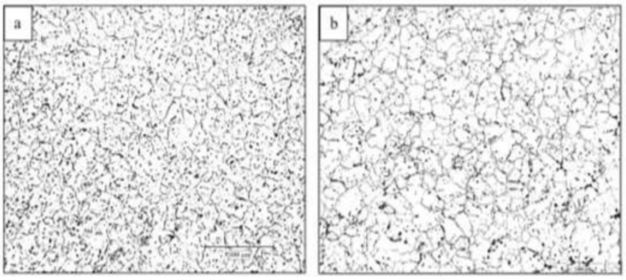

Figure 6: Microstructure at the center of the strip (50X) produced using (a) Double, and (b) Single, impingement feeding systems.

2.4. Surface Roughness Measurement

The success of our pilot HSBC system depends on its ability to produce high surface and bulk quality strip. The feeding system used in this research work relies solely on gravity, viscosity, and surface tension forces to bring down or smoothen out the flow of the molten metal over the moving belt, together with heat extraction rates (belt temperature), and cast thickness, which are also considered important parameters. This in comparison to a more complicated feeding system, installed in Salzgitter/Clausthal caster, involves the use of a complex double weir system, with an electromagnetic brake and an argon jets, used to suppress the free surface oscillations. The surface quality of the produced strip was determined using Nanovea 3D profilometer [13]. The technique is based on measuring the physical wavelength of light and relating it to a specific height. The scanned area was 30mm by 30mm whereas the scan speed was 0.1mms^{-1}. The surface roughness of the strips produced via both feeding systems is shown in (Figures 7 & 8), which lies under 12.5 µm. The bottom surface quality is perfectly flat since molten metal conforms to the shape of the moving belt during casting. For these reasons, only the roughness of the top upper surface is analysed below.

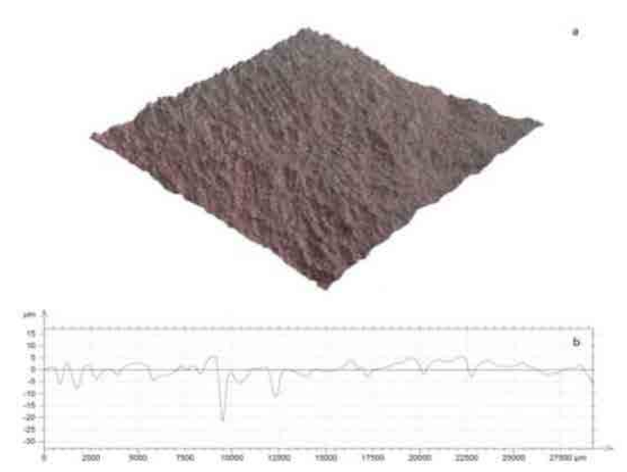

Figure 7: 3D profilometry results of a strip produced using a double impingement feeding system, a) Strip top surface roughness, and b) Strip surface profile.

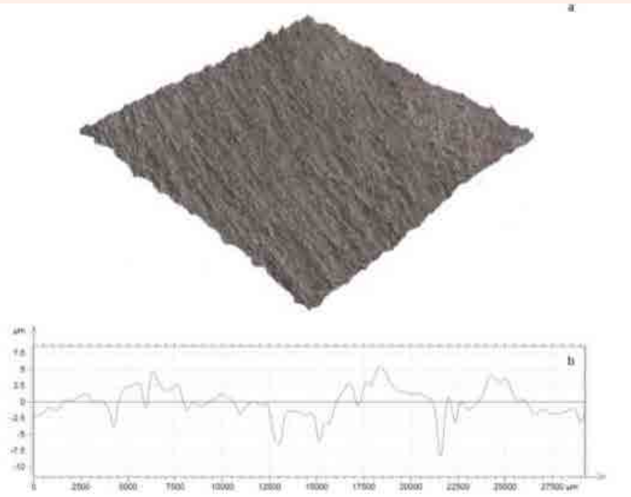

Figure 8: 3D profilometry results of a strip produced using a single impingement feeding system, a) Strip top surface roughness, and b) Strip surface profile.

Conclusion

The following conclusions are drawn from this research study.

a. The molten metal flow behavior in both single and double impingement feeding systems are fundamentally different. The double impingement feeding system tends to moderate or lessen the final impact of the molten metal with the moving belt, resulting in molten metal impinging over the moving belt with reduced velocity, as compared to a single impingement feeding system where the flow is abrupt and sudden, and the flow velocity over the moving belt is comparatively high.

b. The single/double feeding systems rely solely on gravity, viscosity, and surface tension forces, in order to reduce and smoothen the flow of the molten metal over the moving belt. These properties, together with heat extraction rates, and cast thicknesses, are considered of primary importance.

c. For a single impingement feeding system, the molten metal, dispensing from the nozzle slot outlet, is abruptly stopped by the moving belt. As such the molten metal tends to penetrate the quadruple region. However, the opposite is true for double impingement feeding in which molten metal is not entering into the quadruple region.

d. Both HSBC liquid metal feeding systems are viable options, being robust and cost-effective, integrating perfectly in a continuous casting process.

e. The upper surface qualities of the strips produced through single and double impingements feeding systems are superior Additionally, pinholes/blowholes were not detected on the surface of the cast strip, unlike continuously cast products, which possessed defects on their surfaces, and require surface grinding prior to hot rolling [14].

Acknowledgment

The authors would like to acknowledge the financial support received from the Natural Sciences and Engineering Research Council of Canada (NSERC), and the International Advisory Board of supporting companies of the McGill Metals Processing Centre (MMPC), as well as technical support form MetSim Inc., in performing experimental work and high-speed computation using their high speed 288 core computer cluster. The authors would also like to acknowledge the support received from ANSYS Inc. for software licensing to facilitate this research.

Funding

The authors would like to acknowledge the financial support received from the Natural Sciences and Engineering Research Council of Canada (NSERC), and the International Advisory Board of supporting companies of the McGill Metals Processing Centre (MMPC), in carrying out this research. The authors would also like to acknowledge the support received from ANSYS Inc. for software licensing to facilitate this research.

References

1. Celikin M, Li D, Calzado L, Isac M, Guthrie RIL (2016) Horizontal single belt strip casting (HSBC) of Al-Mg-Sc-Zr alloys. Light Metals 2013:1037-1040.
2. Xu M, Isac M, Guthrie RIL (2018) A numerical simulation of transport phenomena during the horizontal single belt casting process using an inclined feeding system. Metallurgical and Materials Transactions B 49:1003-1013.
3. Ge S, Chang S, Wang T, Calzado L, Isac M, et al. (2016) Mathematical modeling and microstructure analysis of low carbon steel strips produced by horizontal single belt casting (HSBC). Metallurgical and Materials Transactions B 47:1893-1904.
4. Guthrie RIL, Isac M (2014) Horizontal single belt casting of aluminum and steel. Steel Research International 85: 1291-1302.
5. Ge S, Isac M, Guthrie RIL (2013) Progress in strip casting technologies for steel; technical developments. ISIJ International 53: 729-742.
6. Spitzer KH, Rüppel F, Viščorová R, Scholz R, Kroos J, et al. (2003) Direct strip casting (DSC)-an option for the production of new steel grades. Steel Research International 74: 724-731.
7. Wans J, Geerkens C, Cremers H, et al. (2015) Belt casting technology experiences based on the worldwide first BCT caster. Technical Contribution to the 46th International Steelmaking Seminar. pp. 111-117.
8. Manual, FIDAP (1998) FLUENT Inc, 10 cavendish court, centerra resource park, lebanon, NH, 3766.
9. Ge S, Chattopadhyay K, Isac M, Guthrie RIL (2012) Mathematical modeling of transport phenomena in horizontal single belt casting (HSBC). 5th International Congress on the Science and Technology of Steelmaking.
10. Niaz U, Isac M, Guthrie RIL (2020) Numerical modelling and experimental casting of 17% Mn-4% Al-3% Si-0.45% C wt-% TWIP steel via the horizontal single belt casting process. Ironmaking & Steelmaking 47: 482-495.
11. Turbulent flow.
12. Xu M, Isac M, Guthrie RIL (2018) Transport phenomena during horizontal single belt casting process using an optimized inclined feeding system. Ironmaking & Steelmaking 45: 878-885.
13. Surface roughness determination using 3D nanovea profilometer.
14. Sengupta J, Thomas BG, Wells MA (2005) The use of water cooling during the continuous casting of steel and aluminum alloys. Metallurgical and Materials Transactions A 36: 187-204.

Citation: Niaz U, Isac MM, Guthrie RIL (2020) The Casting of AA6111 Aluminium Alloy Strips using Single and Double Impingement Types of Liquid Metal Feeding System. J Miner Sci Materials 1: 1018