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Improving Strip Surface Quality of AA6111 alloy using Different Casting Atmospheres for the Horizontal Single Belt Strip Casting (HSBC) Process

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Abstract

The surface quality of as-cast strip is a key factor in the production of strips produced by Horizontal Single Belt Strip Casting process (HSBC). Aluminum alloys were cast on an HSBC simulator, using different casting atmospheres at meniscus region, including preheated air and pure oxygen. The strip's bottom surface was analyzed in order to evaluate the effect of casting atmosphere on strip surface quality. The preheated air or oxygen was injected into the hollowed backwall refractory and was released through the orifices on the bottom of the refractory, close to the back-wall meniscus region. The purpose was to flush out the ambient air entrained above the moving substrate. The possibility of eliminating surface defects caused by air pockets' on the strip's bottom surface and improving surface quality by controlling the casting atmosphere in the meniscus region were confirmed. The surface profiles of the sand-blasted substrates and those of the related strips were analyzed using 3D Profilometry. The interfacial heat fluxes through using an oxygen atmosphere at the upstream meniscus were also enhanced greatly, as compared to the casting process using a graphite coating on the substrate. A novel way for improving strip surface quality with high attendant interfacial heat fluxes is now proposed for the HSBC process.

Introduction

Horizontal Single Belt Casting (HSBC) of strips is a green, near-net shape, strip casting technology, potentially capable of replacing current D.C. aluminum casters, as well as all steel slab caster operations, because of its promising productivity, low energy consumption, low capital cost, and low operating costs [1-3]. The as-cast quality of the strip's bottom surface is a key factor prior to in-line rolling. As-cast strip products must have a satisfactory quality of strip surface, because of the high surface area to volume ratio. "Scalping" the surface to remove surface defects and poor microstructure, as carried out in conventional DC casting and rolling operations, is not possible.

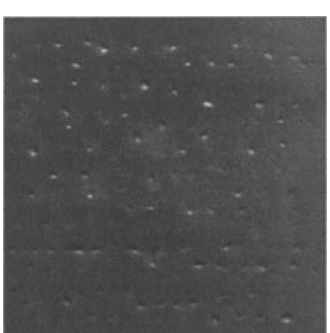
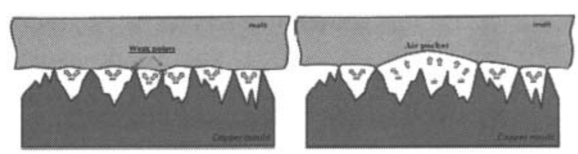


Figure 1. Surface defects generated by air pockets on the bottom surface of aluminum alloy, AA6111 strip.

The air pockets formed on the strip's bottom surface was one of the main surface defects in the HSBC strip casting process for aluminum strip production. Figure 1 gives a photo of the air pockets on the bottom surface of an aluminum strip, cast on a sandblasted bare copper substrate. A mechanism for air pocket formation was proposed in Ref [4]. Thus, when the melt deposits on the top surface of the water-cooled steel, or copper, belt, in Figure 2, the bottom surface of the melt only comes into contact with micro-peaks present on the belt's surface. Melt surface tension prevents the melt from penetrating further into the valleys between the peaks. Air, entrapped in the "valleys", is very rapidly heated by heat transferred from the hot melt above, so that its volume and pressure starts to increase rapidly. Since the melt and peak points in the substrate are connected/joined, the expanded air will tend to lift the melt's bottom surface upwards, so as to form arc curves, while the melt's surface tension will act to balance the extra air pressure by reducing the radii of curvatures. Given that all the "pyramid" valleys underneath the melt were connected to each other, the expanded entrapped air is able to flow underneath the melt and find the weaker points of attachment, where the heated gas can accumulate, and "bubble up". This is believed to be the cause for the many indents appearing on the bottom surface of the strips shown in Figure 1. The air pockets increase the thermal resistance to local heat transfer and reduce the local cooling rate, resulting in a non-uniform microstructure and a varying thickness of strip. The spots where air pockets occur on the bottom strip surface are expected to be crack-initiators during downstream rolling steps. The upper strip surface tends to reflect the lower lever topography, for very thin strips (~1-4mm)



(a) (b)

Figure 2. Proposed mechanism for dimpled surfaces generated by the formation of air pockets. (a) entrapped air starts to expand; (b) melt loses contact with parts of mould, forming air pockets.

According to the previous research work [5], it was possible to eliminate or reduce the air pockets by using a graphite coating on the substrate surface. It is believed that the graphite coating weakens the contact strength at all points of contact, so the expanded air can expand more easily, thereby moderating rises in interfacial gas pressure. However, the graphite coating has a negative influence on interfacial heat transfer, because its thermal conductivity is significantly lower than that of the metal substrate. We observe that cooling rates are lower, solidification times are longer, and productivity is less.
In this paper, casting aluminum alloys using different casting atmospheres in the meniscus region, including preheated air and pure oxygen, in combination with different substrate roughness,

were tested on the HSBC simulator, in an attempt to eliminate air pocket surface defects, without having to use substrate coatings and experience reduced productivities.

Theory

In this paper, since we surmise that the expanding entrapped air can lead to the formation of air pockets, thereby causing surface dimples, and reduced heat fluxes to the substrate, we decided to introduce preheated air and/or pure oxygen into the triple point. Both could possibly act so as to eliminate air pockets (dimples) on the bottom surface of the strip.

Preheated air in the meniscus region

When ambient air is entrapped at the melt-mould interface, its volume expands because of the heat transfer from the melt. The relationship between gas volume, pressure and temperature is ideally described by the ideal gas law;

$$\frac{P_0 V_0}{T_0} = \frac{P_1 V_1}{T_1} \tag{1}$$

here the P, V and T are the air pressure, volume and temperature, respectively. The subscript "0" denotes the average state at room temperature, while subscript "1" means the average state of the entrapped air in the valleys once the air becomes heated by the melt. Similarly, when the hot air atmosphere was introduced to the meniscus region, and cold air was flushed out of the surface valleys and replaced with hot air just before the melt was deposited onto the top of the substrate (~!-2 ms), the initial air temperature in the valleys can be designated as T_{Hot}. In this case, the volume of the entrapped air becomes V_1' once the melt has been deposited on the mould surface. This is described by equation (2).

$$\frac{P_0 V_0}{T_{Hot}} = \frac{P_1' V_1'}{T_1'} \tag{2}$$

here the dashed superscript means the average state of the preheated entrapped air after the melt has deposited on the top of the valleys. The ratio between $V_1'$and V_1 can be calculated by equation (3).

$$\frac{V_1'}{V_1} = \frac{T_0}{T_{Hot}} \frac{T_1'}{T_1} \frac{P_1}{P_1'} \tag{3}$$

Because of the low heat capacity of the air and high heat transfer fluxes from melt to chilled substrate through the air layer, the temperature $T_1'$of the preheated air was close to the air temperature T_1 after the melt was deposited on the top of the valley. As such, the ratio of T_1 and T_1'can be approximated as unity. P_1' and P_1 were the absolute gas pressures in the valleys, ~10^5 Pa, while the pressure difference between P_1' and P_1 was mainly caused by melt surface tension forces, which were in the range 10^2~10^3 Pa. As such, the ratios between P_1' and P_1 could also be approximated as 1. If so, equation (3) can be simplified to:

$$\frac{V_1'}{V_1} \approx \frac{T_0}{T_{Hot}} \tag{4}$$

Normally, room temperature T_0 is about 300K. If the preheated air temperature T_{Hot} reaches 600K, then the expanded volume of the entrapped air will be reduced by about 50% compared to the expanded volume of entrapped air cast at ambient atmosphere. This would also greatly benefit in reducing the size of air pockets formed on the strip's bottom surface. If the preheated air temperature increases to 900K before it enters the melt/substrate interface, its final expanded volume will be only 33% of the expanded volume of entrapped ambient air.

Oxygen atmosphere at meniscus region

Oxygen will react with a fresh melt surface of aluminum to form a coherent aluminum oxide layer on the melt's surface. This oxide layer will insulate the melt and prevent further oxidation. If the valleys on the substrate surface contained pure oxygen instead of air before the valleys are covered by the aluminum melt, the metal would consume some of the oxygen by the oxidizing reaction, Supposing that ΔV is the volume of oxygen within the valleys that reacts with the aluminum melt, the expanded volume V_1 of the entrapped oxygen in the valleys will be described as equation (5):

$$\frac{P_0 (V_0 - \Delta V)}{T_0} = \frac{P_1 V_1}{T_1} \tag{5}$$

Compared to equation (1), the final expanded volume of the entrapped oxygen will become less than the expanded volume in equation (1), reducing the possibility of forming air pockets on the strip bottom surface.

Experiments

HSBC simulator

A schematic view of the HSBC simulator, designed at McGill University is given in Figure 3. It comprises a moving chill substrate, a stationary refractory-lined tundish as the melt holder, fitted with a slot nozzle for metal delivery, and a compression spring system to propel the substrate laterally under the stationary tundish. When preheated air was needed at meniscus region, a propane flame was used to preheat the compressed air. The preheated air or pure oxygen (cold) was delivered to the tundish nozzle refractory through a stainless steel tube which was covered by a woven glassy fiber outside, so as to act as a heat insulation layer. Figure 4 gives the configuration of the HSBC tundish nozzle system near the meniscus region. The backwall refractory was drilled to be hollow inside, connecting to the external stainless steel tube. The preheated air or oxygen was released on to the substrate surface, near to the meniscus region through three rows of orifices of ~ 1mm diameter, and distributed in the transverse direction through the bottom of the backwall refractory at intervals of 3mm, so as to form a gas curtain and flush out the ambient air drawn in by the moving substrate. The cooling substrate was fabricated from high-purity copper (99.99% +), 800mm long, 110mm wide and 12.7mm thick. The substrate contained five 62mm×62mm removable, pure copper blocks, located along the mid-section, so as to allow different surface roughnesses and/or textures to be studied under identical casting conditions for optimizing strip surface quality. In the experiments described, a melt of aluminum was poured into the tundish. After about two seconds delay for turbulence dissipation, the compressed spring was then released, the attached hammer striking and propelling the substrate to move under the tundish at almost constant speed. The tundish slot nozzle was automatically opened after the substrate started to move, so melt passed through the nozzle slot, and was deposited onto the moving substrate, so as to form a thin strip. In this way, the melt casting and solidification on the real HSBC caster could be simulated, and the strip's bottom surface quality, cast on different topographical surfaces of copper blocks, could be compared under identical casting parameters, such as casting temperature, casting speed,

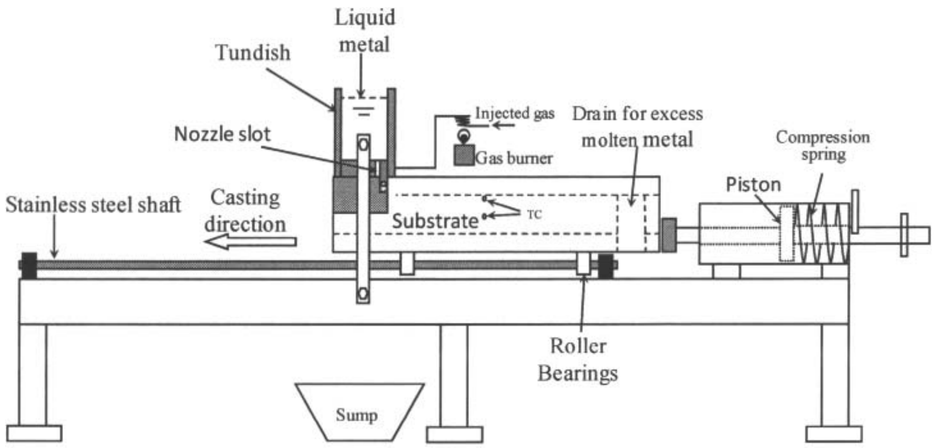


Figure 3. Schematic view of horizontal single belt strip casting simulator.

strip thickness, alloy chemical composition, etc.

According to our previous study, the meniscus gap between the bottom of the backwall refractory and the moving substrate surface dominates meniscus behavior [6]. Melt backflow problems can occur if the vertical gap is > 1.3mm. In order to simplify the research work in this paper, the meniscus gap in the experiments was always preset to be 1.0 mm, so as to form a stable meniscus profile.

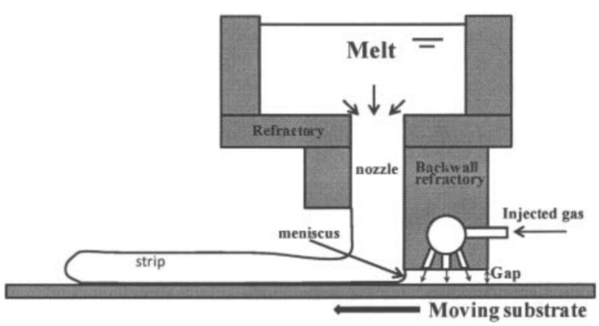


Figure 4. Configuration of backwall. Injected gas was introduced through orifices set in the bottom of the backwall.

In order to evaluate the interfacial heat fluxes during melt solidification on the chilled substrate, two T-type thermocouples, which consist of pure copper and constantan wires, were embedded into the copper blocks at different vertical distances below the copper top surface, so as to measure local temperature variations. These were used as data for calculating transient interfacial heat fluxes via the Inverse Heat Conduction Problem (IHCP) [7]. Because the substrate was made of oxygen-free electric-grade ultra-pure copper (99.99%), the copper block itself could be used as part of the T-type thermocouple circuit. This gave extremely short response times. The constantan wires were shielded with a stainless steel sleeve containing Teflon insulator. These were pushed through precisely drilled, small holes from the copper substrate bottom, and then held in contact with the copper substrate using compressed springs. Copper wires were fixed to the copper substrate's bottom to complete the electrical circuit.The distance of one thermocouples' joint to the copper block's top surface was 0.55mm, while the other was 3.70mm. The milli-voltage signals, generated at the junction between the constantan wire and copper substrate corresponding to the actual temperatures there, were recorded with a data acquisition system operating at a frequency of 500Hz.

Substrate surface roughness

The effects of substrate surface profiles or roughnesses on the strip surface quality were also considered in the paper. The copper blocks' surfaces were blasted by different sand media in order to obtain uniform surface profiles with different roughness. Then the copper surface profiles were scanned by a NANOVEA 3D profilometer, giving results shown in Figure 5. The sand materials used in the sandblasting machine and related copper block number are listed in Table 1.

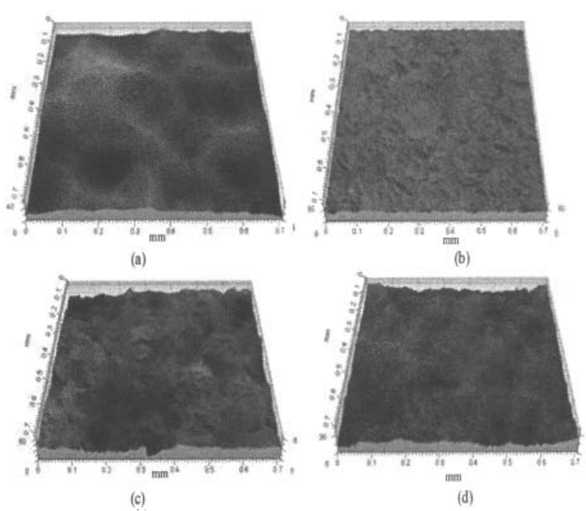


Figure 5. 3D surface images of the copper blocks, sandblasted by different sand materials. (a) by steel shot; (b) by aluminum oxide; (c) by Garnet grit; (d) by stainless steel shot.

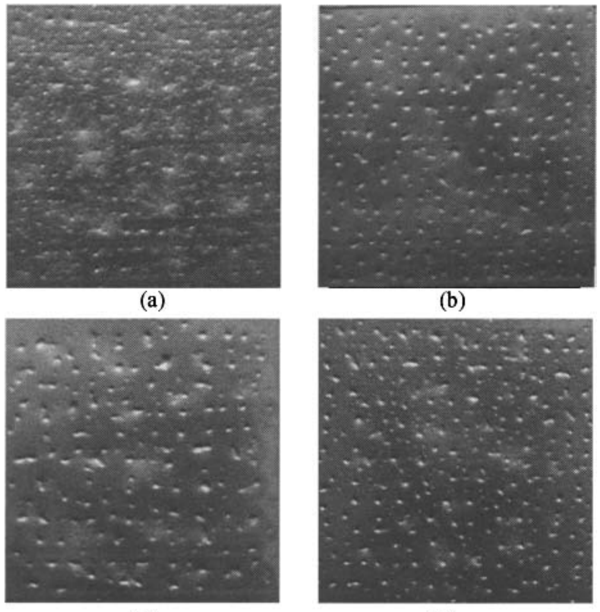
Table 1. Sand materials and related copper blocks' name and surface roughness

Sand materials	Size of the sand	Copper blocks' roughness, μm	Copper surface number
Steel shot	20~35 mesh	5.59	Surface –I
Aluminum oxide	45-140 mesh	3.36	Surface –II
Garnet grit	54 mesh	7.35	Surface –III
Stainless steel	50~140 mesh	3.59	Surface –IV

Experimental Results

Strip casting using preheated air atmosphere in meniscus region

A propane gas burner was used to heat up the spiral air tube for preheating the air inside, which entered the backwall refractory and was released into the meniscus region. Although the combustion temperature of the propane gas was more than 1000°C, and the injected air could be preheated up to 700°C inside the spiral coil, the preheated air lost its heat rapidly when it was transferred from the spiral coil into the backwall refractory, owing to the low air flow rate and low heat capacity of air. When the air flow rate was 5 LPM (measured at 25°C), the temperature of the air flowing out of the backwall refractory near the meniscus was only 130°C. Increasing the air flow rate to 20 LPM (measured at 25°C), increased the air temperature at the orifices to 350°C ~400°C. At higher air flow rates (> 25LPM), the preheated air pressure and outflowing velocities of the gas streams became too high, causing disruption of the meniscus, forming huge bubbles within the melt. As such, an air flow rate of 20 LPM (at 25°C) was adopted for the casting experiments.



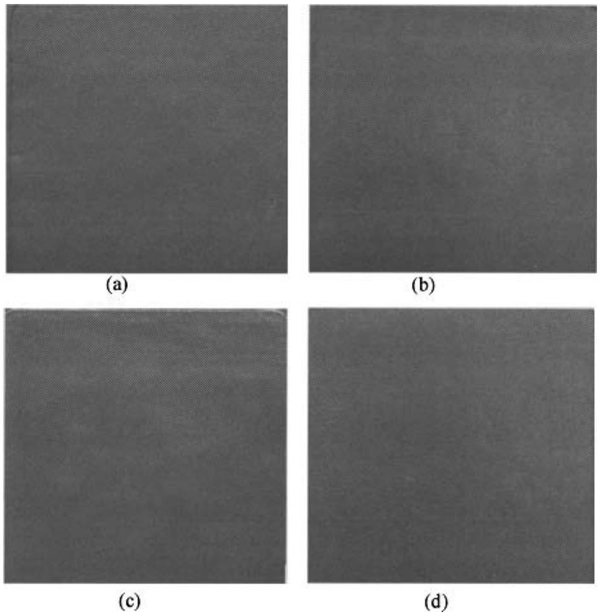
(a) (b) (c) (d)

Figure 6. Photos of bottom surfaces of aluminum strip cast using preheated air in the meniscus region. (a) on Surface-I; (b) on Surface-II; (c) on Surface –III; (d) on Surface –IV.

Figure 6 gives the photos of the bottom surface of aluminum strip cast on different surfaces of copper blocks, using the HSBC simulator. It was found that many small air pockets were formed on the strip's bottom surfaces, which were similar to samples cast on the same substrates shown in Figure 1, without preheated air in the meniscus region. The preheated air was not able to reduce air pocket surface defects. The likely explanation is the lack of heat capacity of the gas, versus that of the copper substrate, causing the heat pulse to be absorbed before the strip was contacted by the aluminum melt. Further work is needed to resolve this issue.

Strip Casting using oxygen in the meniscus region

Pure oxygen was injected into the gas tube and streamed out of orifices in the backwall refractory, so as to maintain an oxygen atmosphere in the meniscus region. It was found that when the oxygen flow rate was 10LPM, the number and depth of the air pockets on the strip bottom surface were remarkably reduced, in comparison to strip samples cast in ambient air. When the oxygen flow rate was increased to 30LPM, the air pockets on copper surface–I and copper surface –IV also almost disappeared, as shown in Figure 7. On copper surface-II and mould surface-III, the strip bottom surface also became smooth with some extremely shallow marks of the air pockets. The depth of the air pockets was less than 100μm, which would not be harmful for the downstream hot and cold rolling.



(a) (b) (c) (d)

Figure 7. Photos of aluminum strip bottom surfaces, cast within oxygen atmosphere at meniscus region with a flowrate of 30LPM; (a) on Surface-I; (b) on Surface-II; (c) on Surface –III; (d) on Surface –IV.

When the oxygen flow rate increased to more than 40LPM, oxygen gas blew into the meniscus, forming bubbles within the melt, similar to the phenomenon observed with high flowrates of preheated air. Therefore, an upper oxygen flow rate of 30LPM was chosen for these casting experiments.

Figure 8 displays a typical 3D bottom surface image of the aluminum strip sample cast on the copper block sandblasted by steel shot using an oxygen atmosphere in the meniscus region. In addition to the dendrites and grain boundaries observed in the image, the outgrowths of the contact points occurring between the melt and the copper substrate were also found. The protuberant mountainous areas (shown by the red areas) represent the solidified historical sags, where the melt deposited on the top of the copper block and penetrated into the valleys between the peaks. This occurred since the air was pre-flushed out by pure oxygen and this oxygen was partly consumed reacting with the aluminum melt. The expansion of the surplus oxygen in the valleys lifted the melt bottom surface to form the outgrowths, but the gas pressure was not apparently sufficient to break through weak contact points and form pocket defects. Because of this, the final strip surface quality was much improved.

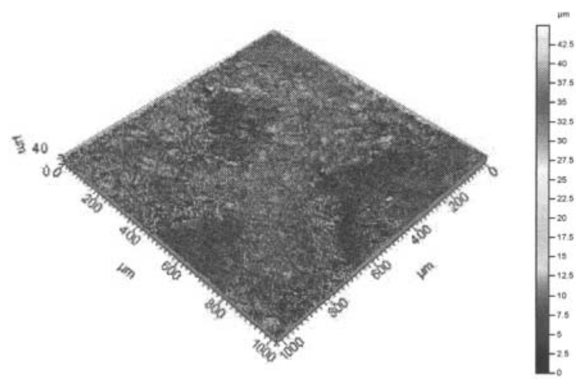


Figure 8. 3D image of the bottom surface of aluminum strip, cast on copper blocks (Surface-I) in the presence of an oxygen atmosphere in the meniscus region. The surface of the copper block was sandblasted by steel shots.

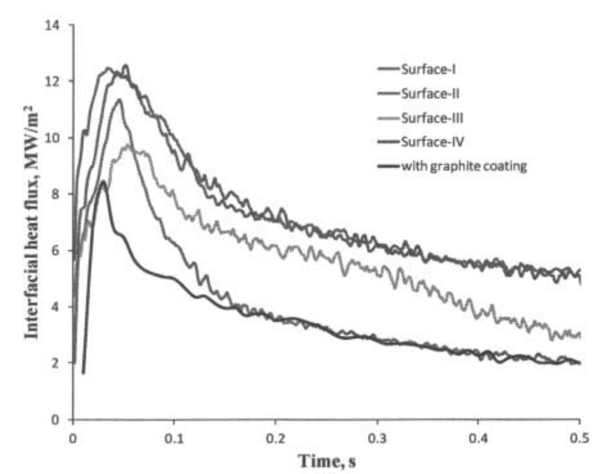


Figure 9. Interfacial heat flux curves when casting aluminum alloy strips on a copper substrate in the presence of an oxygen atmosphere in the meniscus region.

Interfacial heat fluxes

Interfacial heat fluxes were calculated by the IHCP method using the temperature-time data acquired from the T-type thermocouples embedded in the copper blocks. As mentioned, a graphite coating was used to eliminate the air pocket defects in our former research work. The interfacial heat flux curve when casting an aluminum melt on a graphite coated copper substrate was used as a reference curve (black), in order to evaluate the heat transfer using different casting atmospheres. When the visible surface defects of air pockets formed on the bottom surface of the strip, the extra air layer inside the air pockets increased the thermal resistance during heat transfer and lowered the local interfacial heat flux. Normally the air pockets were randomly distributed on the bottom surface, producing non-repeatable heat flux curves in the casting experiments. Therefore, only the interfacial heat fluxes obtained on the aluminum strip samples with flat bottom surfaces, using an oxygen atmosphere in the meniscus region, were considered in this section. Figure 9 gives the typical interfacial heat flux curves. The oxygen flow rate was 30LPM. It is clear that using an oxygen atmosphere without a graphite coating increased ab-initio interfacial heat fluxes greatly. On the copper blocks of Surface–II and Surface–IV, the maximum heat flux reached $12 MW/m^2$, much higher than the peak heat flux using a graphite coating on a copper substrate surface. The increased heat flux will help to increase the cooling rate and improve the strip's surface quality and attendant microstructure. Higher cooling rates and shorter melt solidification times also lead to higher casting speeds, allowing for higher productivities for industrial HSBC casters.

Summary

The use of preheated air or pure oxygen atmosphere in the meniscus region during HSBC casting was tested in this paper. It was found that preheated air was not able to eliminate the bottom surface defects generated by air pockets. However, using an oxygen atmosphere in the meniscus region proved to be an efficient way to improve aluminum strip bottom surface quality in the HSBC process, while the interfacial heat flux was simultaneously enhanced by avoiding using a graphite coating on the copper substrate. This points to a potential way to increase the productivity of an industrial HSBC caster for aluminum alloys.

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