**Ab-initio Predictions of Interfacial Heat Fluxes in Horizontal Single Belt Casting (HSBC), Incorporating Surface Texture and Air Gap Evolution**

Roderick I. L. GUTHRIE, Mihaiela ISAC and Donghui LI

McGill Metals Processing Centre, McGill University, 3610 University Street, Montreal, QC, H3A 2B2, Canada. E-mail: mihaiela.isac@mcgill.ca

(Received on April 21, 2010; accepted on August 10, 2010)

The purpose of this study was to develop ab-initio mathematical and computational models, aimed at predicting instantaneous heat fluxes when a liquid metal or alloy first comes into contact with a colder substrate during near net shape casting processes. Fully computational models were developed to determine whether the measured instantaneous heat fluxes associated with the strip casting of aluminum alloys on copper substrates could be inferred from first principles. For this, strip cast aluminum surfaces were physically analyzed using a 3-D Profilometer, so as to provide the detailed surface textural information needed for the mathematical modeling. It was shown that the modeled mould surface characteristics, such as pyramid height and number of contact points per mm$^2$, are critical in determining the peak heat fluxes achieved during metal/mould contact. Reducing pyramid heights and/or increasing the number of contact points are beneficial in enhancing interfacial heat fluxes.

The mechanism of air pocket formation was also explored through mathematical modeling. The volume expansion of entrapped air was deduced to be the main reason for “air pockets” forming on the strip’s bottom surface. A new method for predicting air gap evolution was proposed in which a fixed grid system and an anisotropic thermal conductivity model were used. The computational models allow for various scenarios to be effectively studied, and for experimental curves to be matched against “predicted” curves. Finally, copper moulds with macroscopically textured surfaces were tested, and it was found that these surfaces were effective in expelling entrapped air to adjacent grooves, and in enhancing overall interfacial heat fluxes.

**KEY WORDS:** interfacial heat flux; horizontal single belt casting; mathematical modeling; roughness; macroscopically textured mould; air pockets; air gap evolution.

1. Introduction

The Horizontal Single Belt Casting (HSBC) of strip is a friction-free, near net-shape, continuous process of high cooling capability.$^{1–3}$ The process is ideally suited to replace current slab caster operations, given its matching productivity, “green” characteristics, and lower capital and operating costs. One of the most important characteristics of this machine is the interfacial heat transfer between the melt and the moving water-cooled belt. However, this heat extraction process is affected by the way the melt contacts the belt. This, in turn, affects the machine’s productivity. Predicting the instantaneous heat flux by thermal models is a practical design problem for casting operations. The objective of the present work was to develop a thermal model in which instantaneous heat flux curves could be predicted from first principles$^{4,5}$ and the mechanisms of strip surface cavity defects could be explored.

In HSBC casting, the microscopically “rough” belt surfaces ($R_s \approx 5–14 \mu m$) not only provide contact points for melt nucleation and heat transfer, but can also interact with the down flowing melt to entrap air at the triple point meniscus, where the melt first meets the belt. This results in occasional air pockets which can freeze in on the strip’s bottom surface, leading to surface blemishes and significant local decreases in the interfacial heat flux. Similarly, melt shrinkage during solidification can also increase the topological thickness of the air gap at the melt-belt interface, and lead to surface blemishes, compounding the problem of a first principles, or ab-initio, thermal analysis. Nonetheless, this new approach is far more satisfactory than just ascribing an empirical instantaneous interfacial heat transfer coefficient, as in the past, to represent the complex set of factors at play (surface roughness, topography, thermal properties of mould and substrate, casting temperature, mould temperature, etc.) when the melt contacts a cooling substrate.

To meet this challenge, the mathematical modeling of solidification in the HSBC casting process requires a realistic characterization of the heat transfer phenomena at the metal/belt interface. It is necessarily a multi-phase phenomenon. Given the improvements in the speed of micro-com-
puter calculations and in the methods of numerical simulations, it now becomes possible for the heat transport phenomena between the melt and belt, including solidification, to all be predictable from first principles. For this, we need to solve the general heat transfer equations for the particular set of melt and boundary conditions involved.

2. Strip Casting Experiments

In order to provide all the detailed physical information for the mathematical modeling, such as belt surface profile, strip bottom surface profile, belt/melt contact points, and instantaneous heat fluxes during casting and solidification, some exploratory experimental measurements needed to be carried out, prior to the mathematical modeling work.

2.1. Experimental Apparatus

A schematic view of the HSBC simulator, designed at McGill University, is given in Fig. 1. It comprises a moving chill substrate (of Cu or Fe), a stationary refractory-lined tundish for melt containment/holding, fitted with a slot nozzle for metal delivery, and a compression spring system to propel the substrate laterally under the stationary tundish. The cooling substrate was fabricated from high-purity copper (99.99% H11001). It measured 800 mm long, 110 mm wide and 12.7 mm thick. The substrate contained five 62 mm H11003 removable pure copper blocks located in the mid-section, so as to allow different surface roughnesses and/or textures to be studied under identical casting conditions. In the experiments described, a melt of aluminum was poured into the tundish. Following a 2 s delay, the compressed spring was then released, the attached hammer striking and propelling the substrate under the tundish at almost constant speed. The tundish slot nozzle was automatically opened by the striking hammer, 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 mould, could be compared under identical casting parameters, such as casting temperature, casting speed, alloy chemical composition, etc.

2.2. Surface Characterization

A NANOVEA 3-D Profilometer was acquired to scan the matching surfaces of the moulds and strips. The technique provides a contactless topological measurement of any surface, by using the principle of superior white light axial

chromatism. The white light passes through an objective lens and the photons have a high degree of chromatic aberration. The objective lens’ refractive index will vary in relation to the wavelength of the light. In effect, each separate wavelength of the incident white light will refocus at a different distance from the lens (different height). When the measured sample is within the range of possible heights, monochromatic points will be focalized and form the image. A spectral analysis is done using a diffraction grating. This grating focuses each wavelength to a different axial position, intercepting a line of CCD’s. These, in turn, indicate the position of the maximum intensity and allows for direct correspondence to the height position.

The accuracy of the 3-D Profilometer in the vertical direction was ~60 nm, and the minimum scanning step in the horizontal direction was down to 1.3 μm, giving sufficient resolution to analyze the matching mould and strip surfaces’ characteristics.

**Figure 2** gives an example of a 3-D image of a sandblasted copper mould surface. **Figure 3** gives a 3-D image of the complementary pure aluminum strip bottom surface, cast on that copper mould. From the strip’s bottom surface,
the 3-D grain boundaries, and even the directions of dendrites’ growths, are all visible. Within the surface grains, fine cone-shaped outgrowths can also be seen. We have attributed these unexpected outgrowths to the contact points between the melt and the bottom copper mould, during casting. With the melt shrinking away from the mould during solidification and the entrapped air expanding, the strip’s bottom surface pulls away from the mould surface, but the contact points between melt/mould remain connected to each other, resulting in the elongated cone-shaped outgrowths appearing on the strip’s bottom surface.

By counting the number of cone-shaped outgrowths per unit area, using the post-processing 3D Professional software, the average number of contact points was found to be 261 points/mm² when a pure aluminum melt, 1.5 mm thick, was iso-kinetically cast on to the sand-blasted copper mould surface, so as to form a strip. The dynamic changes in the interfacial air gap could also be deduced by analyzing the heights of the cones and the instantaneous heat fluxes. For this, the statistical results of the mould and strip surface characteristics by the 3-D Profilometer provided the data base needed for developing a realistic fundamental mathematical model capable of predicting interfacial heat transfer between the solidifying melt and the chill copper mould from first principles.

2.3. Measuring Interfacial Heat Fluxes Using T-type Thermocouples

Two thermocouples were embedded into the copper moulds at different vertical distances below the mould surface, so as to measure local temperature variations, and to use these as data sources for calculating transient interfacial heat fluxes by the Inverse Heat Conduction Problem (IHCP). The distance of one thermocouples’ joint to the mould’s top surface was 0.55 mm, while the other was 3.70 mm. In order to compare measured interfacial heat fluxes with mathematical predictions, especially during the first moments of contact between the melt and the (cold) mould, extremely rapid response times were required for the thermocouples.

T-type thermocouples consist of pure copper and constantan wires. 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 thermocouple circuit together with a constantan wire, if T-type thermocouples were considered for the experiment. Constantan wires were accordingly shielded with a stainless steel sleeve containing a Teflon insulator. These were pushed through precisely drilled, small holes in the bottom of the copper substrate, and then held in contact with the copper substrate using compressed springs. Pure copper wires were fixed to the copper substrate’s bottom to complete the electrical circuit. The compressed springs always pushed the constantan wires against the copper during casting, maintaining good electrical contact. In this way, the junction between the constantan wire and copper materials at the contact point generated mille-voltage signals corresponding to actual temperatures at those locations within the substrate. The mille-voltage signals were recorded with a data acquisition system at 500 Hz. Steady state temperature readings deriving from this custom made T-type thermocouple system were verified using standard K-type thermocouples.

Figure 4 displays typical interfacial heat fluxes obtained in experiments, in which a melt of pure aluminum was cast onto a sand-blasted copper mould having an average surface roughness of 4.5 μm. The final strip thickness was about 1.5–1.6 mm. Within 6 to 8 ms, the heat flux curves reached their maximum point, and then decreased. These results showed that this custom made T-type thermocouples responded to mould temperature variations very rapidly, recording maximum heat fluxes very close to the first moments of melt/mould contact. These results were incidentally much faster than in our previous research work on the same simulator. There, we reported ~150 to 200 ms for heat fluxes to reach their maxima when using exposed K-type thermocouples.

3. Theory and Numerical Method

3.1. General Governing Equation

For ideal contact of a melt with a cooling substrate, our simulator experiments approach iso-kinetic feeding conditions. For such a situation, the melt and substrate are moving at the same speed, so that lateral convective terms may be discounted. In such cases, heat is extracted vertically. Based on this situation, and using a moving Eulerian co-ordinate system, travelling at \( U_h \), we can write the governing differential heat transfer equation for the transfer of heat from a “stagnant” liquid metal to a copper chill mould, in terms of the general transient heat conduction equation (Fourier’s Second Law). Previously, we modelled the interfacial area by postulating the presence of a gas film, of variable thickness, separating the melt from the mould. We were able to derive standard equations showing the importance of a very thin gas film separating the liquid metal from the substrate. However, in reality, we have three phases in intimate contact at the interface (liquid metal, gas, and a copper substrate), so specific forms of Eq. (1) will apply to all three phases, in the microscopic region separating the melt and the chill copper substrate, where they all co-exist:
There, the melt is seen hanging between two parallel runnings: the melt’s surface tension and substrate contact can be idealised according to its local temperature. When the melt was first deposited on the mould surface, and all the melt was in the liquid state because the superheat of the melt had not yet begun to be released into the chill mould. Since the copper surface was not wetted by the aluminum melt, only the pyramid’s tip of the copper mould surface was presumed to be in contact with the melt, and the first moment of melt-substrate contact can be idealised according to Fig. 6. There, the melt is seen hanging between two parallel-running peaks, distance \( h \) apart. The melt’s sag, \( d_{\text{sag}} \), depends on the melt’s surface tension \( \sigma \), and its metallostatic pressure \( \Delta P \), for a non-wetting substrate. The radius of melt curvature \( R \) for these conditions is therefore:

\[
R = \frac{\sigma}{\Delta P} = \frac{\sigma}{\rho g h} \quad \text{..................(3)}
\]

where \( S_t \) is the source term, which, for the molten metal, is related to the latent heat released during solidification, together with the solid fraction, \( f_s \). \( S_t \) is zero for the gas phase and for the copper substrate phase. Hence, for the melt:

\[
S_t = \frac{\partial (\rho L f_s)}{\partial t} \quad \text{..........................(2)}
\]

The symbols, \( \rho \), \( C_p \), \( k \), in Eq. (1), represent the respective densities, specific heats and thermal conductivities of the three phases (molten metal, gas, copper). \( T \) is the local temperature in each phase, while \( t \) represents the time passed since the liquid metal first contacts the substrate.

### 3.2. Mould Geometry

The real sand-blasted copper mould surface resembled an irregular mountainous region with many uneven summits that contacted the melt and supported the whole of the forming strip as solidification took place. This is depicted in Fig. 2. In order to reasonably model and evaluate the heat flow between the melt and copper mould, the complex topographical copper surface had to be simplified to some typical profile of regular geometry. In this paper, we idealised the actual surface topology into a regular array of three dimensional pyramid-shaped “mountains” with shallow valleys in between. These shallow valleys were filled with air. Figure 5 provides a schematic view of the idealised mould surface topography, showing the type of meshing used in the model.

Thus, according to the analysis by the 3D profilometer, the average number of contact points between the melt and substrate was found to be 261/mm² and the average peak height was 4.5 \( \mu \)m. Because of symmetrical geometry, only one eighth of one pyramidal domain, incorporating the three phases, needed to be selected as the computational domain for numerical simulation.

#### 3.3. Melt Bottom Surface Profile

At the moment of melt contact with the substrate, the melt was deposited on the mould surface, and all the melt was in the liquid state because the superheat of the melt had not yet begun to be released into the chill mould. Since the copper surface was not wetted by the aluminum melt, only the pyramid’s tip of the copper mould surface was presumed to be in contact with the melt, and the first moment of melt-substrate contact can be idealised according to Fig. 6. There, the melt is seen hanging between two parallel-running peaks, distance \( \lambda \) apart. The melt’s sag, \( d_{\text{sag}} \), depends on the melt’s surface tension \( \sigma \), and its metallostatic pressure \( \Delta P \), for a non-wetting substrate. The radius of melt curvature \( R \) for these conditions is therefore:

\[
R = \frac{\sigma}{\Delta P} = \frac{\sigma}{\rho g h} \quad \text{..................(3)}
\]

For example, according to Eq. (4), \( d_{\text{sag}} \) for a 1.5 mm thick aluminum strip cast onto a substrate surface with peaks 61 \( \mu \)m apart, is equal to 0.02 \( \mu \)m. This calculation shows that melt sag is practically negligible compared to the span between neighboring peaks on the mould’s surface. As such, a flat bottom surface of solidifying metal at the interface should be expected, and was observed, in practice.

#### 3.4. Material Properties

In this work, pure molten aluminum was deposited onto the copper mould. In our computations, melt thicknesses were specified as 1.5 mm, in order to compare the predicted interfacial transient heat fluxes with the experimental results in Fig. 4. Thermal properties, such as density, conductivity, and specific heat of the aluminum melt and copper mould are listed in Table 1. The casting temperature of the aluminum melts was \(~680°C\); latent heat of the pure aluminum melt was released over a slight range of temperature (660–655°C) for the sake of iteration convergence. The latent heat of pure aluminum is 397 kJ/kg. The physical properties of the entrapped air were treated as being variable, according to its local temperature.

#### 3.5. Modeling for Air Layer Evolution

The cone-shaped outgrowths found on the bottom surface of the aluminum strip were created during solidification. When the melt was first deposited on the mould surface, the melt’s bottom surface was flat, as shown in Fig. 7(a). Then, as the entrapped air in the pyramidal valley became hotter and hotter, its volume expanded. Aluminum also shrank away from the copper substrate during solidifi-

\[
\frac{\partial (\rho C_p T)}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + S_t \quad \text{..........................(1)}
\]


cation, which presumably increased the interfacial gap still further. However, the melt and mould still adhered to each other at the contact points shown in Fig. 7(b). “δ(t)” is the time-dependent distance because of air layer evolution. Considering the moving boundary of the mushy melt’s bottom surface, in combination with the transient solid fraction forming, and the release of latent heat within the melt, makes modeling the evolution of the real air layer at the melt/mould interface extremely complex. The question of how to model an evolving air gap became a critical point in trying to predict the whole heat transfer process from first principles, during HSBC processing.

In this paper, a new method for modeling an evolving air layer is proposed: the heat transfer through a growing air layer was transformed to the case of heat flow through a thin air layer of fixed thickness, in accordance with the theory of coordinate transformation. Inside the entrapped air valley, a thin layer, thickness δ₀, was selected, shown in the shadow area in Fig. 7(c). The melt’s bottom surface was kept the same as a flat surface, as at the initial moment of contact. The domain of the thin air layer δ₀ was considered as the increasing air gap layer. At the moment of contact, t = 0, δ(t) = 0, the air layer has the same size as δ₀, like in Fig. 7(c); at t = t, the size of the real air layer increased to δ₀ + δ(t). In the domain of the air layer δ₀, a new coordinates system, x’, y’, z’ was defined as: x’ = (δ₀/δ₀ + δ(t))x, y’ = y, z’ = z. x’ represents the vertical direction. Then dx’ = ((δ₀ + δ(t))/δ₀)dx, dy’ = dy, dz’ = dz. In the other domain except of the air layer δ₀, we simply define: x’ = x, y’ = y, z’ = z, then dx = dx’, dy = dy’, dz = dz’. Inserting these equations into the general governing Eq. (1), the governing equation for the air layer domain can now be described by Eq. (5), while the governing equation for the other two domains become Eq. (6),

\[
\frac{\partial (\rho C_p T)}{\partial t} = \frac{\partial}{\partial x'} \left( k \left( \frac{\delta_0}{\delta_0 + \delta(t)} \right)^2 \frac{\partial T}{\partial x'} \right) + \frac{\partial}{\partial y'} \left( k \frac{\partial T}{\partial y'} \right) + \frac{\partial}{\partial z'} \left( k \frac{\partial T}{\partial z'} \right)
\]

\[
\frac{\partial (\rho C_p T)}{\partial t} = \frac{\partial}{\partial x'} \left( k \frac{\partial T}{\partial x'} \right) + \frac{\partial}{\partial y'} \left( k \frac{\partial T}{\partial y'} \right) + \frac{\partial}{\partial z'} \left( k \frac{\partial T}{\partial z'} \right)
\]

It can be seen that Eqs. (5) and (6) are similar to the general governing Eq. (1), except that the thermal conductivity has anisotropic characteristics, as seen from Eq. (7), while the computational domain remains in the original boundary layer of δ₀. In this way, the effect of air layer evolution on the heat transfer process could be predicted by solving the general governing Eq. (1) by considering an anisotropic thermal conductivity for the gas layer δ₀, rather than considering the melt boundary as moving upwards. As such, a single static computational mesh could be used during all iterations, and this greatly simplified the modeling work. So the anisotropic conductivity of the equivalent stationary gas layer becomes;

\[
k'_{\text{air layer}} = \begin{bmatrix}
  k \left( \frac{\delta_0}{\delta_0 + \delta(t)} \right)^2 & 0 & 0 \\
  0 & k & 0 \\
  0 & 0 & k
\end{bmatrix}
\]

### 3.6. Boundary Conditions

As only the first one second of the heat transfer process following melt deposition on the chill mould was considered in this mathematical modeling, the radiation and natural convection from the top surface of the melt was ignored. The bottom of the chill copper mould on the HSBC simulator was insulated by refractory, so the heat flux through the bottom of the computational domain was set to zero. On all the other surfaces of the pyramidal section and in the melt above, the heat flux was set to zero because of its symmetrical boundary condition. The melt initial temperature was set to be the casting temperature, 680°C, while the mould temperature and air temperature at the moment of contact,

### Table 1. Physical properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, Kg/m³</th>
<th>Specific heat, J/Kg K</th>
<th>Thermal conductivity, W/m K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure aluminium</td>
<td>2700</td>
<td>1200</td>
<td>207</td>
</tr>
<tr>
<td>Copper mould</td>
<td>8920</td>
<td>380</td>
<td>398</td>
</tr>
</tbody>
</table>

Fig. 7. Schematic view of air layer evolution, (a) at first contact moment; (b) air gap began to increase after first moment of contact; (c) computational domain for mathematical modeling.
were set to 20°C.

3.7. Computational Method

Because of the symmetry of the computational domain, only one eighth of the heat transfer, related to one pyramidal region, was modeled. GAMBIT software was used for meshing the computational geometry, using tetrahedral hexahedral, combining with pyramid and wedge elements; the total number of elements was about 61 000. A power law scheme was adopted for the spatial discretization of the energy equation. The transient term was discretized using a first order implicit scheme. The iterative time step was set as 1 ms, and a convergence criterion of temperature field’s residual was set at less than $1 \times 10^{-15}$. The predictions were made using the ANSYS FLUENT V12 software package.

3.8. Computational Results

3.8.1. Typical Heat Fluxes Predicted for a Constant (Inert) Air Layer vs. Experimental Results

Using mathematical modeling, the interfacial heat flux without any evolution in the interfacial air layer was first considered, and the pyramid width was set as 61 μm. This choice corresponds to 261 contact points/mm² and matches the surface data obtained with the 3D profilometer. The pyramid height was 4.5 μm, equal to the average copper mould roughness. The predicted heat flux curve is compared with the experimental result in Fig. 8. It can be seen that the predicted heat flux with no air layer evolution was about twice as high as the experimental result during the first 330 ms of contact. This predicted heat flux extraction on an aluminum melt of 1.5 mm thick would lead to complete solidification within 200 ms. In practise, it takes about 600 ms to release all the latent heat, according to the experimental result. We believe this was due to a growth in the air layer thickness, increasing the interfacial thermal resistance and reducing interfacial heat flows.

The maximum experimental heat flux obtained in these experiments was about 11.0 MW/m², which happened at 6–8 ms after the moment of contact. Theoretically, the maximum heat flux should occur at the first moment of contact of the melt with the copper chill mould. In reality, any thermocouple needs a short time to respond to the mould temperature variation, no matter how fast it is. So far, it is impossible to measure the interfacial heat flux at the first moment of contact and we believe mathematical modeling is the only way to explore the truth. By mathematical modeling, the predicted interfacial heat flux was about 13 MW/m² at the first moment of contact, which is close to the experimental result. It was thereby verified that at t = 0, the melt contacts the chill mould on the contact points, and the melt’s bottom surface was smooth, without cone-shaped outgrowths.

3.8.2. Air Layer Evolution During Solidification

The evolution in the air layer thickness played an important role in modifying the interfacial heat transfer between the melt and the copper mould. Expansion of entrapped air, melt shrinkage during solidification, and mushy melt surface tension variations, all affect the growth of the air layer. Furthermore, the air pockets on the aluminum bottom surface were distributed randomly, so it is not practical to model the whole irregular copper surface taking into consideration all the factors mentioned above. Rather, a trial and error method was adopted, so as to determine the kinetic tendency for air layer growth.

At first, three different air layer evolutionary paths were considered, as shown in Fig. 9. In Line-I, the size of $d(t)$ grew linearly from zero to 2 μm in 0.5 s, then remained there, at 2 μm; for Line-II, $d(t)$ grew linearly from 0 to 6 μm in 0.5 s, then remained constant; Line-III, $d(t)$ grew linearly from 0 to 4.5 μm in 0.5 s, then again held at 4.5 μm. Figure 10 gives the related predicted interfacial heat fluxes. In the case of $d(t)$ following the Line-I proposition, the predicted interfacial heat flux curve was still much higher than the experimental result, meaning that the real air layer growth is more than that depicted in Line-I. For the case of $d(t)$ following Line-II, the predicted heat flux became much lower than the experimental heat flux, pointing out that the average air layer evolution was less than 6 μm. In the case of Line-III, the predicted heat flux curve followed the experimental heat flux curve during the first 100 ms, but then the predicted heat flux decreased continuously and became much lower than the experimental results.

By trial and error, Line-IV $d(t)$ is proposed: for this, $d(t)$ increased from 0 to 0.9 μm linearly in 100 ms, then increased to 1.8 μm more slowly over a period of 0.6 s. This was followed by a rapid increase to 5 μm at 1 s, as shown in Fig. 9. The corresponding predicted interfacial heat flux curves vs. the experimental results are given in Fig. 10. As
seen, the “fitted” heat flux curve then followed the experimental heat flux curve very well. Figure 11 gives 3D images of aluminum solid fractions forming above one eighth of a pyramid at different moments after first contact. The total melt thickness was 1.5 mm, so only the evolution of the solid fraction near to the melt/mould interface is displayed in Fig. 11. It can be seen that the solidification was initiated at a pyramid tip and that the solidification shell grew rapidly, such that after 15 ms, the bottom surface becomes a coherent solid, as the nucleating portions meet each other.

3.8.3. The Effect of Mould Surface Characteristics on Initial Heat Fluxes

The interfacial heat flux at the first moment of contact is a representative value for gauging heat transfer between a melt and a chill mould. Mould surface characteristics, including pyramid height and the number of contact points per square millimetre, were considered. The number of contact points per square millimetre could be deduced from the base width of a pyramid. Figure 12 gives the predicted results of the interfacial heat fluxes at the first moment of contact. It was found that the pyramid height affects the interfacial heat flux greatly, because the higher the pyramid, the more entrapped air is kept at the melt/mould interface. When the pyramid height was 40 μm, the initial heat flux was about 1.7–3.5 MW/m², while the initial heat flux could be increased to 12.8–13.3 MW/m² when the pyramid height was reduced to 4.5 μm.

The number of contact points also affects the interfacial heat flux at the first moment of contact. When the mould surface was rough, and pyramid heights were 40 μm, the initial interfacial heat flux could be increased from 1.7 to 3.5 MW/m², a more than 100% increase, by changing the number of contact points from 100 to 2,500 points/mm². However, when the mould surface was smooth and the pyramid height was reduced to 4.5 μm, the initial interfacial heat flux was only increased by 3.7% on increasing the number of contact points from 100 to 2,500 points/mm².

Figure 13 gives the experimental interfacial heat flux curves which were measured by casting aluminum melt onto a polished copper substrate and a sand blasted copper mould.

3.8.4. Proposed Mechanism for Air Pocket Formation on the Bottom Surfaces of Strips

The air pockets observed to form on the strip’s bottom surface was one of the main surface defects in the HSBC
strip casting process. The possibility of entrapped air expansion at the interface was studied using mathematical modeling. The average air temperature between the pyramids jumped to 330°C from room temperature, in less than 1 ms, following first contact. Considering air as an ideal gas, the increasing temperature will cause the air volume and air pressure to increase. For example, when the pyramid height was 4.5 μm and the width of pyramid base was 61 μm, the volume of entrapped air will increase from $1.12 \times 10^4$ to $2.29 \times 10^4 \mu m^3$ in less than 1 ms, supposing the air pressure is kept at atmospheric pressure. Since the melt and mould are stuck together at the points of contact, the expanded air will tend lift the melt's bottom surface to form a curve. Melt surface tension forces then increase and prevent further expansion. In fact, given that all the pyramid valleys underneath the melt were connected to each other, it was possible for the entrapped air to flow freely underneath the melt, thereby finding the weakest points for breaking through.

At weak points, we propose that the melt detached from the mould peak points, resulting in the sudden increase in the span between neighbouring contacted points. Mean-time, the interfacial heat flux at detached areas decreased greatly, causing a slowing in the local solidification process owing to the sudden increase in local interfacial thermal resistance. Since the radius of curvature of the detached area was increased, the melt surface tension became insufficient to balance the entrapped air pressure, compared to uncompromised melt/mould areas, elsewhere. The local melt surface would curve upwards, allowing neighbouring expanded air to flow in and accumulate, finally forming an air pocket on strip’s bottom surface, as depicted in Fig. 14. The air pockets work like a sump to accommodate the expanded air, and to slow down the air layer evolution. For this reason, the predicted result of LINE-IV in Fig. 9 gave a slowly increasing curve of air gap layer after the first contact moment rather than a sudden jump. It was also found that in some strip casting experiments, the air pockets could even break through the melt to form a hole in the as-cast strip.

Our prior work has emphasised the value of using a graphite spray coating on the mould surface, as this was effective in eliminating the air pockets and improving the surface quality of the aluminum strip. Because the graphite does not wet the aluminum, all the contact points at interface were weakened. Once the entrapped air pressure went up, the melt would detach from the mould easily, and this is beneficial in allowing the expanded air to escape. By analyzing the aluminum strip bottom surface cast on a graphite coated copper mould, no remarkable cone-shaped outgrowths were observed. This is probably the reason why graphite coatings largely eliminate air pockets from the bottom surface of aluminum strips. However, the downside to a graphite coating is a substantial decrease in the interfacial heat flux, owing to the additional thermal resistance of the graphite coating.

4. Use of Textured Substrates for Enhancing Heat Fluxes

According to the research work above, smoothing the mould surface, or reducing the pyramid height, will reduce the entrapped air at the melt/mould interfaces and increase the interfacial heat transfer greatly. In order to obtain high interfacial heat fluxes and to eliminate air pockets forming on strip’s bottom surface, novel macroscopically textured copper mould surfaces were proposed, built, and tested. Figure 15 provides a 3D image of the textured copper mould surface, taken by the 3D Profilometer.

The copper blocks were stamped with regular triangular grooves. The grooves cross each other, at 45° to the casting direction. All the grooves were connected together to form channels for accommodating or expelling the entrapped air at the melt/mould interfaces. The copper mould surfaces were ground down by sandpaper up to 1200 grit, so as to form smooth top surfaces, in order to reduce the air layer gap between the melt and mould in these regions. Two different patterns of grooves were made: in pattern (a), the depths of the grooves were 0.20 mm; while in pattern (b), the grooves depths were 0.25 mm. The distance of neighboring notches in both pattern (a) and pattern (b) was 1.52 mm.

Figure 16 gives the interfacial heat fluxes obtained in casting experiments. In order to evaluate the interfacial heat fluxes cast on these textured copper moulds, the result of heat flux casting on a sand-blasted copper mould with a graphite coating was also given as a reference marker. Aluminum strip thickness was 5.0 mm, casting temperature was 680°C. When the melt was cast onto the sandblasted copper substrate, which had a graphite coating, then within 30 ms...
The interfacial heat flux reached a peak value of about 8.4 MW/m², after which the heat flux started to decrease slowly. When the melt was cast on the macro-textured copper pattern (b), the interfacial heat flux reached a maximum of 21 MW/m² at 6 ms after which the heat flux decreased quickly to about 15 MW/m²; the transient heat flux then slowed as latent heat was released in the melt mushy zone. At 0.18 s, the interfacial heat flux suddenly dropped to less than 5 MW/m², no doubt because of contraction and deformation of the strip during solidification, followed by detachment of the strip from the copper substrate surface. When an aluminum melt was cast on textured copper pattern (a), the interfacial heat flux curve was similar to pattern (b), but the maximum heat flux point became higher, at 23.3 MW/m². At 0.13 s, the strip detached from the copper surface, leading to a sudden drop in the heat flux curve. More textured copper patterns and the surface qualities of the aluminum strips are reported in Ref. 16).

5. Conclusions

(1) A 3-D mathematical model for predicting interfacial heat transfer in the HSBC process has been developed on the basis of a first principles analysis of heat conduction.

(2) The entrapped air layer apparently grows non-linearly, in the case of casting a 1.5 mm aluminum melt. The air layer evolution could be described by Line-IV.

(3) Pyramid height affects interfacial heat fluxes greatly. Reducing entrapped air volume will result in a significant enhancement of interfacial heat transfer.

(4) When the mould surface was rough, increasing the number of contact points will further increase interfacial heat transfer. When the mould surface was smooth, and pyramid heights low, interfacial heat fluxes became insensitive to the number of contact points between the melt and the mould.

(5) Textured copper moulds were tested for enhancing interfacial heat transfer and regularising the quality of cast strip surface.

REFERENCES