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STUDIES OF FLUID FLOW AND MENISCUS BEHAVIOR DURING HORIZONTAL SINGLE BELT CASTING (HSBC) OF THIN METALLIC STRIPS

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Abstract

Horizontal Single Belt Casting of strips is a green strip casting technology, potentially capable of replacing current DC and slab caster operations. As-cast strip bottom surface quality is a key factor for the near-net shape casting operations. The meniscus behavior at the triple point of gas, substrate, and liquid metal, where the melt first touches the moving belt is important to surface quality, as is the way in which the melt behaves while in subsequent contact with the chill substrate. In this paper, meniscus behavior and fluid flow mechanisms were analyzed and predicted through mathematical modeling, using COMSOL software. It was found that the backwall gap, combined with melt vertical inlet velocity through the tundish nozzle slot, and the belt speed, dominated meniscus behavior. The backwall gap must be pre-set to be less than the critical gap size in order to prevent melt "back flows" and leaking accidents. The mathematical modeling of meniscus behavior and fluid flow was further supported by physical water modeling, and was validated through HSBC simulator tests using aluminum alloys.

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 caster, as well as steel slab caster. This is because of its promising productivity, low energy consumption, and low capital and operating costs [1-3]. The as-cast strip bottom surface quality is a key factor before the in-line rolling process. The as-cast strip products must have a satisfactory quality of strip surface, because the high surface area to volume ratio makes it uneconomical for "scalping" the product surface in order to remove surface defects, as carried out in conventional DC casting and rolling operations. Figure 1 provides a schematic view of HSBC process. A small gap must be kept between the backwall of the tundish refractory lining and the moving belt during the strip casting process for free running of the belt, and to avoid possible contamination, or scratching of the belt's upper surface by the tundish refractory. Therefore, a stable melt/air free surface, or meniscus, will be formed during casting. The melt flows down through a simple nozzle slot and changes its flow direction to the horizontal, as it flows and freezes on the water cooled belt. The stable air/melt interface is called the forward meniscus. Near, or at the meniscus, the surface layer of liquid metal meets the air and then the moving chill substrate. It then begins to form the initial solidified shell on the melt's bottom in "contact" with the cooling belt. This initial solidification is important in determining the final strip's bottom surface quality. The oscillation of the meniscus, entrapment of air bubbles at the triple point, or oxidation of the melt at meniscus, would generate strip surface defects, such as air pockets, micro-crack, and a non-uniform microstructure of the strip [4, 5].

In order to understand the meniscus behavior and fluid flow mechanisms in HSBC processing, mathematical modeling using COMSOL software was developed, so as to predict the movement of the free air/melt interface and the flow patterns in the near meniscus region. The mathematical modeling of meniscus behavior and fluid flow was later verified by a physical water model of HSBC casting, and was subsequently also validated through HSBC simulator tests using aluminum alloys.

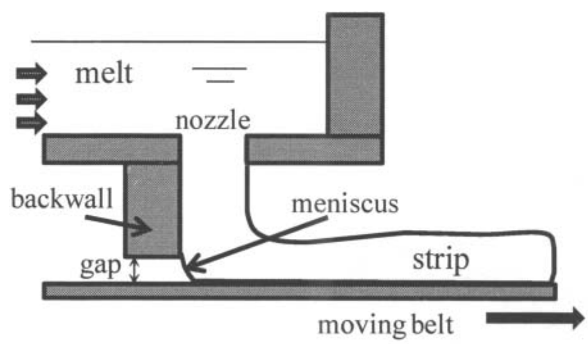

Figure1. Schematic view of the meniscus in the HSBC process.

Mathematical model

The melt flow and air/melt meniscus behavior in HSBC processing were studied by solving the continuity equation and the Navier-Stokes equations, coupled with the "phase field" method. Since the metal was still in its liquid state near the meniscus region because of its casting superheat, the heat transfer and solidification of the melt were ignored for this simplified model. Also, aluminum alloys cast in ambient air were considered in this paper.

Continuity and incompressible Navier-Stokes equations

$$\nabla \cdot \mathrm{u} = 0 \quad (1)$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla[-p\mathbf{I} + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^{\mathrm{T}})] + \rho g + \mathrm{G}\nabla\phi \quad (2)$$

The last term on the right hand side of equation (2) is a body force due to melt surface tension, G is the chemical potential (J/m^2), and ϕ is the dimensionless phase field variable. g is the gravity vector.

Phase Field Method

In order to model the flow of two immiscible fluids and to trace the air/aluminum melt interface, where the exact position of the interface is of interest, the phase field method was adopted. This entails solving the equation of the phase field variable ϕ [6]. The equations governing the interface dynamics of a two-phase flow can be described by the Cahn-Hilliard equations, shown below, as equations (3) and (4).

$$\frac{\partial\phi}{\partial t} + u \cdot \nabla\phi = \nabla \cdot \frac{\gamma\lambda}{\varepsilon^2}\nabla\Psi \tag{3}$$

$$\Psi = -\nabla \cdot \varepsilon^2\nabla\phi + (\phi^2 - 1)\phi \tag{4}$$

Here ϕ is the dimensionless phase field variable, varying from 1 to -1, while the variable Ψ is referred as the phase field help variable. The Cahn-Hilliard equations force ϕ to take a value of 1 or -1, except in a very thin region at the fluid-fluid interface. As such, the position of the air/melt interface would be described by the iso-value curve of ϕ=0. The volume fraction of the two immiscible fluids can be described by $(1 + \phi)/2$ and $(1 - \phi)/2$. The term λ in equation (3) represents the mixing energy density, while ε is a capillary width that scales with the thickness of the interface. The variable γ is the mobility, which determines the time scale of the Cahn-Hilliard diffusion, and must be large enough to retain a constant interfacial thickness, but small enough so that the convective terms are not overly damped. In COMSOL Multiphysics, the mobility was determined by a mobility tuning parameter χ, which was a function of the interface thickness, shown in equation (5). In the present paper, the mobility tuning parameter χ was set as 1.

$$\gamma = \chi\varepsilon^2 \tag{5}$$

The two parameters of λ and ε are related to the surface tension coefficient via equation (6).

$$\sigma = \frac{2\sqrt{2}}{3}\frac{\lambda}{\varepsilon} \tag{6}$$

An aluminum melt was considered in the present work, with a surface tension of 0.914N/m, and a melt density of 2,380 Kg/m^3 [7].

Numerical method

The multiphase flow problem, involving a moving air/moving melt interface in HSBC processing, was simplified to a 2-dimensional fluid flow problem, and was solved by COMSOL Multiphysics software. The transient phase field variable was initialized first for setting the phase field variable ϕ which varied smoothly across the initial interface, and was 1 or -1 anywhere else. Then the momentum equations and continuity equation were solved, coupled with the phase field variable equations. The value of the phase field variable was used to compute the air/melt interface curvature and the surface tension force for the source term in the Navier-Stokes equation. Note that triangular elements were used in meshing the computational domain. The maximum mesh size was less than 0.3 mm in the entire region involving the interface between the air and the melt.

Experiments

In order to verify the results of the mathematical modeling, experiments were carried out on an HSBC simulator and also on a water model of the HSBC metal delivery system.

The HSBC simulator comprised a moving chill substrate, a stationary refractory-lined tundish with a rectangular slot nozzle for melt delivery, and a compression spring system to propel the substrate laterally under the stationary tundish. Once the substrate starts to move, the tundish nozzle slot opens automatically and melt drops down through the nozzle slot and deposits on the substrate. A high speed video camera was placed to the side, behind the tundish, as shown in Figure 2. The camera lens was adjusted to be parallel to the copper substrate surface, so that we could observe the movements of the melt meniscus through the backwall gap. The camera could record a movie at 300 frames per second. This was fast enough to capture the instantaneous air/melt interface oscillation during the strip casting process.

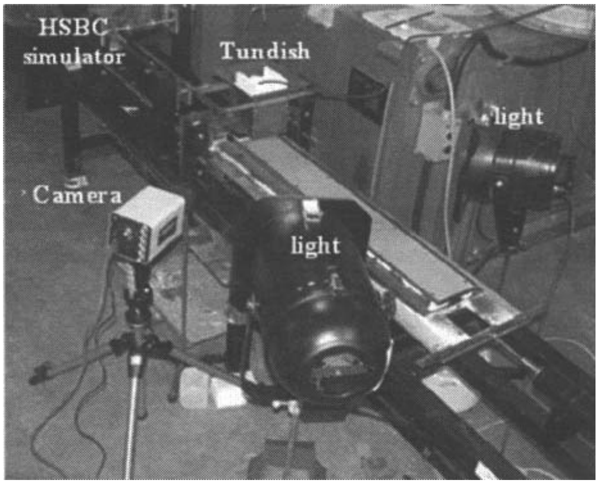

Figure 2. HSBC simulator with high speed video camera system.

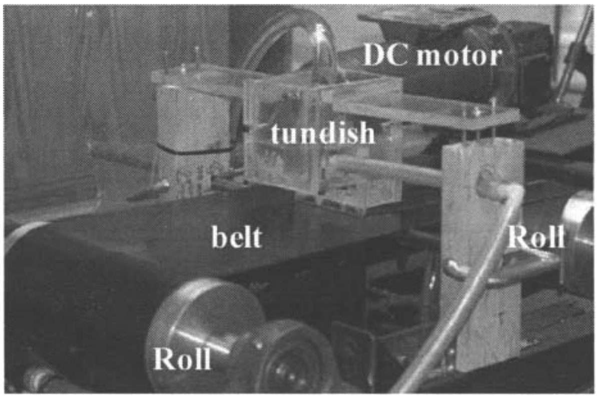

Figure 3. Water modeling system for the HSBC process.

A full scale water model of the simulator system was also built in order to model the flow patterns in the HSBC metal delivery system, as shown in Figure 3. An endless rubberized belt, maintained under tension, circulated around a series of rolls continuously. Plexiglas was used to fabricate a tundish with a rectangular slot nozzle (82mm wide×2.5mm thick) set in the bottom of the tundish. Gravity dominates the fluid flow through the HSBC tundish nozzle system, while inertial forces control the fluid flow pattern developing along the moving belt. As such, the same Froude number and same Reynolds number must be satisfied in order to use the water model to simulate the flow of aluminum in the HSBC simulator. Since the geometry of the water modeling system was 1:1 to the HSBC simulator, the Froude criterion was automatically met. The dynamic viscosity of aluminum is 0.001338 Pa·s, and its density is 2,380Kg/m^3. Water with a density of 1,000Kg/m^3, and a dynamic viscosity at 48°C of 5.6×10^{-4}Pa·s, provides a perfect match of Reynolds Numbers between the two systems. As such, the flow patterns generated within the molten aluminum in the HSBC simulator could be studied by the water model system.

Discussion

Predicted flow patterns in the melt and meniscus behavior

Figure 4 displays predicted air/melt interface movements when the aluminum melt is allowed to flow through the nozzle slot and deposit onto the moving belt. The gap size between the backwall and the moving belt was set at 0.8 mm, the belt speed was 0.4m/s, and the average melt inlet velocity was specified as 0.8m/s. At 0.02s, the melt had dropped down sufficiently to touch the belt; the hydraulic impact spread the melt outwards, with most of the melt flowing with the belt downstream. However, a small part of the melt flowed backwards, entering the narrow gap between the backwall of the melt delivery system and the moving belt; at time=0.03s, the melt penetrated about ~3-4 mm into the gap, owing to the impact static pressure. A little later, the viscous drag forces generated in the fluid by the moving belt, dragged the penetrated melt back into the main downstream flow. The meniscus profile then oscillated for a few milleseconds, and then became stable.

Figure 5 (a) shows the flow pattern near the meniscus region after the melt flow had stabilized. The gap size for the backwall of the delivery system was 0.9 mm and the melt inlet velocity was 0.9m/s. The black curves show the meniscus profile and the top air/melt free surface profile. It was found that the melt flow near the meniscus region was slow, and that most of the incoming melt flowed in the downstream direction close to the upper air/melt free surface; the moving belt only dragged melt in its immediate vicinity downstream by viscous drag forces. A small counterclockwise re-circulatory flow, together with another small upper circulatory pattern, flowing clockwise, were formed between the upper main flow and the belt, The Figure 5(b) displays the static pressure field, related to the flow pattern in Figure 5(a). The pressure near the backwall meniscus region was the highest, owing to the hydraulic impact of the upper incoming flow. The high pressure pushed the melt towards the backwall gap, but the melt surface tension force was able to balance the over-pressure and form a stable meniscus profile.

Backwall gap vs. meniscus behavior

For a practical HSBC strip casting process, the vertical distance, or gap size, between the base of the backwall and the belt, may be somewhat variable during belt rotation, owing to slight variations in belt properties, or slight imperfections in the two (or three) rolls of the HSBC caster itself. We therefore modeled the effects of different gap sizes on meniscus behavior, using mathematical modeling. The backwall gaps were chosen to be between 0.8mm ~ 1.3mm. It was found that increasing the size of the backwall gap would lead to deeper penetration length of the melt entering the backwall gap.

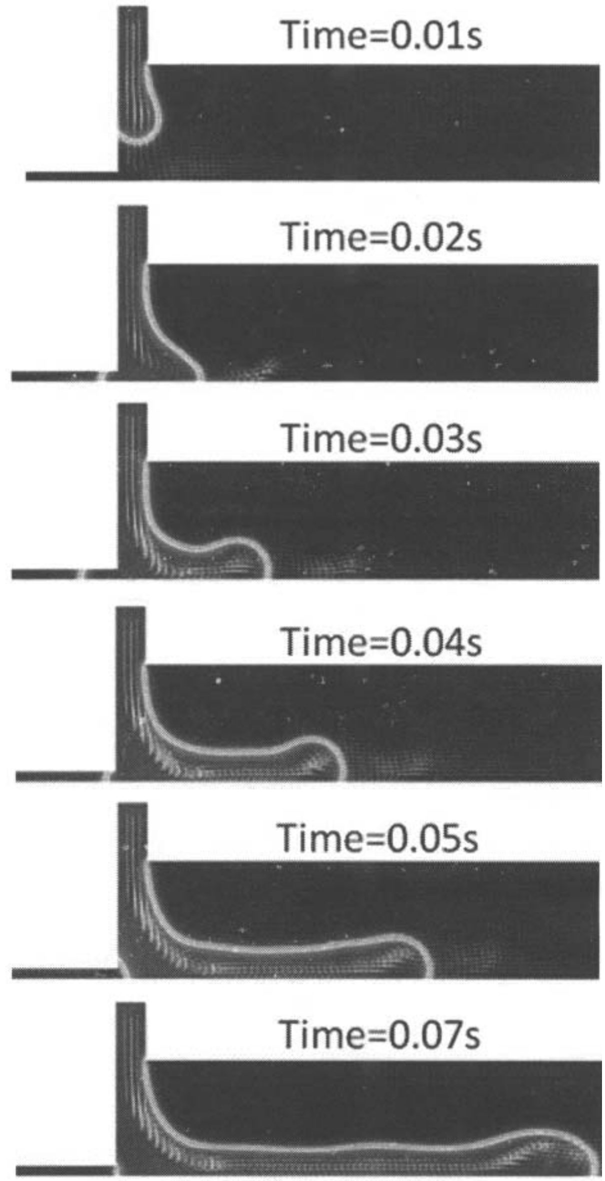

Figure 4. Predicted images of air/melt interface profile with velocity field at different moments under tundish nozzle, melt inlet velocity=0.8m/s, backwall gap 0.8mm, belt moving speed 0.4m/s.

For example, when the gap size was increased to 1.1mm under melt inlet velocity of 0.8m/s, and a belt casting speed of 0.4m/s, the melt would backflow, penetrating into the gap for about 10 mm, before the melt retreated back to the main flow, compared to a maximum penetration length of 3 ~ 4mm in Figure 4. When the gap size became more than 1.1mm, the melt would flow upstream, out of the backwall gap, forming a melt puddle in the front of the refractory backwall, as shown in Figure 6. The melt puddle would keep growing, resulting in a leaking accident in strip casting production. The minimum backwall gap size for preventing melt leaking from the bottom of the backwall can be defined as the Critical Gap Size(CSG). Before the strip casting starts on HSBC caster, the backwall gap needs to be adjusted below the CGS corresponding to the casting parameters.

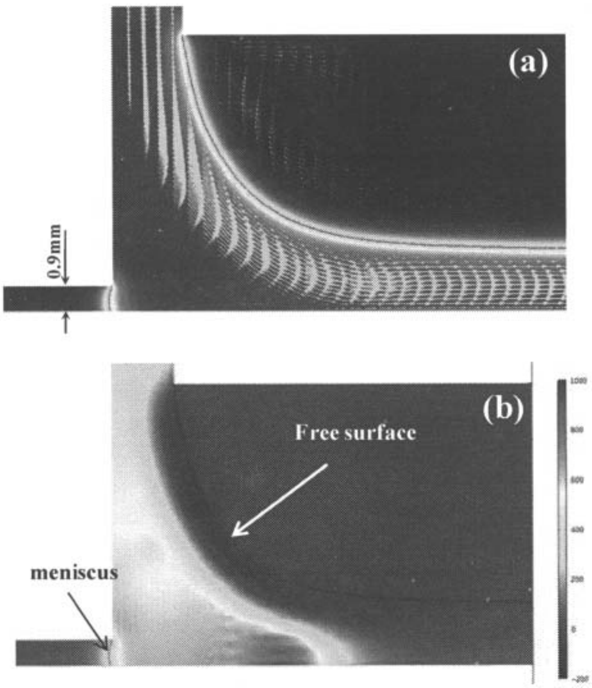

Figure 5. Predicted meniscus and free surface profile, backwall gap is 0.9mm, inlet velocity is 0.9m/s and belt moving speed 0.4m/s. (a) flow patter; (b) pressure, Pa.

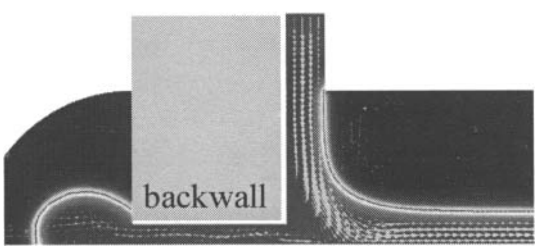

Figure 6. Predicted melt flow pattern when the backwall gap size was 1.3mm, and belt moving speed was 0.4m/s at 0.06s after casting started.

Melt inlet velocity vs. meniscus behavior

The variation of melt level in the HSBC melt delivery system will change the hydraulic head over the nozzle slot. This, in turn, affects the melt inlet velocity through the slot nozzle and also changes the strength of the hydraulic impact and pressure when the melt touches down onto the moving belt. Different inlet velocities of aluminum melt were tested by mathematical modeling. It was found that when the melt inlet velocity increased, the critical size of backwall gap would decrease accordingly, as shown in Figure 7. For example, when the melt inlet velocity was 0.8 m/s, the critical gap size of the backwall was 1.1mm; when the melt inlet velocity was increased to 1.0 m/s, the pressure near the meniscus region increased greatly, and the critical gap size was decreased to 0.8mm. When the inlet velocity was 1.2m/s, the critical gap would reduce to 0.6mm. In order to reduce the melt inlet velocity flowing through the nozzle slot, the melt level should be kept as low as possible to reduce the melt's potential head.

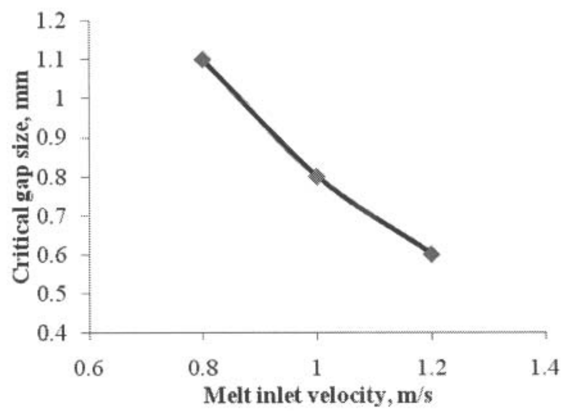

Figure 7. Melt inlet velocity vs. Critical Gap Size (CGS), belt moving speed = 0.4m/s.

Belt moving speed vs. meniscus behavior

The moving belt will drag the adjacent melt to flow in the belt's moving direction by viscous drag forces. This is of benefit in reducing melt penetration under the backwall. The effect of belt speed on meniscus behavior was also studied in the present mathematical modeling work. When the gap size was 1.3mm and melt inlet velocity was 0.8m/s, backflow will happen if the belt speed is 0.4m/s, as shown in Figure 6. However, when the belt moving speed increases beyond 0.6m/s, the penetrated melt under the backwall gap will be dragged back into the main flow after about 0.1~0.2s of the start of a cast. Figure 8 displays the predicted meniscus profile with fluid velocity field, after the melt flow has stabilized, in comparison with the predicted results in Figure 6.

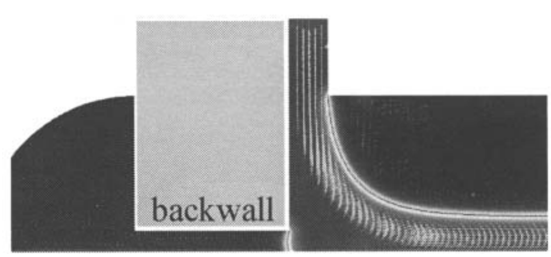

Figure 8. Predicted stable meniscus profile and fluid velocity field when the backwall gap size is 1.3mm, and belt moving speed is 0.6m/s, for comparison with the results predicted in Figure 6.

Experimental results

In the water modeling experiments, the dimension of the nozzle slot was 82mm×2.5mm, the same size as in the casting experiments on the HSBC simulator, and the pilot scale caster at McGill University. The average inlet velocity through the slot nozzle under different water levels in the tundish was measured, and is shown in Figure 9. Since the water modeling had identical Reynolds number and Froude number as the HSBC simulator, the average melt velocity flowing through the nozzle slot could be directly deduced from water modeling experimental results. These flow rates depend on the melt level in the HSBC melt delivery system.

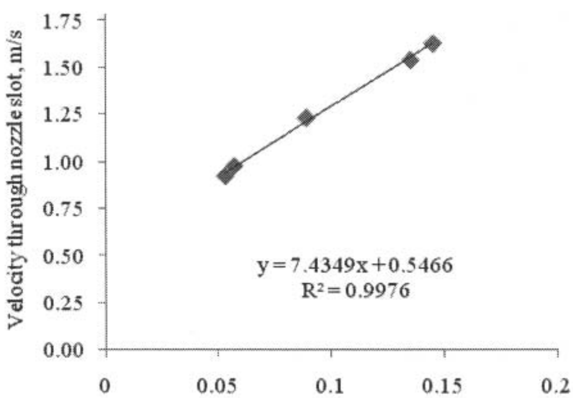

Figure 9. Potential head of water in tundish vs. fluid velocity through the slot nozzle, in the water modeling experiments.

Aluminum melts were next cast on the HSBC simulator, and the high speed video camera, running at 300 fps, was used to record the behavior of the melt meniscus. Superheat of the melt in the "tundish" was kept at 30°C. The melt potential head in the tundish was 0.05m. The casting speed was 0.4m/s. The thickness of the refractory backwall was 10 mm, the same size as that used for the mathematical modeling. Figure 10 gives a photograph of the stable meniscus, as taken through the backwall gap during a casting experiment. The backwall gap was pre-set at about 0.7~0.8mm. The melt did not penetrate through the backwall gap, and form a stable meniscus profile underneath the tundish nozzle. Figure 11 presents photos of how the melt leaking from the bottom of the backwall after the substrate started to move. The photos were taken at 0.06s, 0.10s, 0.25s respectively. The backwall gap was set to be 1.1~1.2mm. It was clearly observed that when the melt dropped onto the substrate surface, the hydraulic impact pushed the melt upstream rapidly out through the gap, under the backwall, forming a big melt puddle. The melt puddle kept growing and growing until the moving substrate reached the end of its stroke. The experimental results agreed well with the results predicted by mathematical modeling.

Summary

The phase field method, coupled with the continuity and Navier-Stokes equations were successful in predicting the air/melt interface movement and meniscus behavior for the HSBC process. The backwall gap, combined with the melt inlet velocity through the tundish slot nozzle and the belt's speed, all were important in governing the meniscus behavior. Reducing the size of backwall gap, and/or reducing the melt level, and/or increasing the belt speed, were all beneficial in preventing melt backflow through the gap between the backwall and the belt. The formation of a stable meniscus, and meniscus line, is a necessary condition to the HSBC process. The predicted results are in good agreement with the experimental observations.

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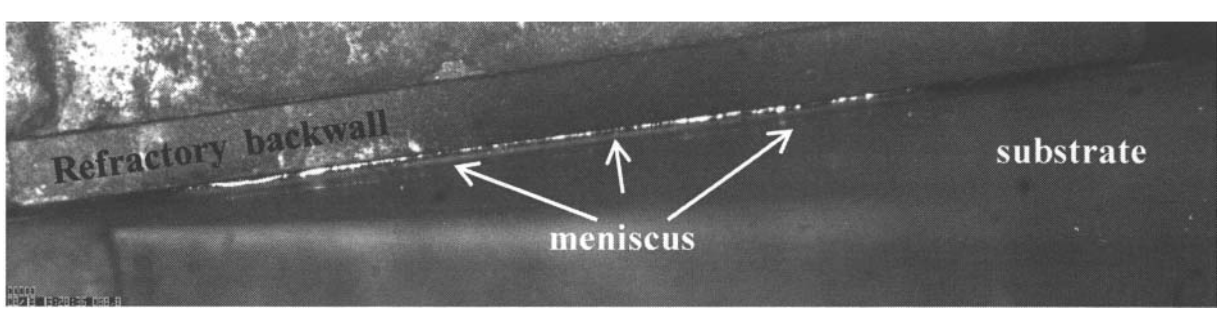

Figure 10. Photograph of a stable meniscus when the backwall gap was 0.7~0.8mm, and the substrate belt speed was 0.4m/s.

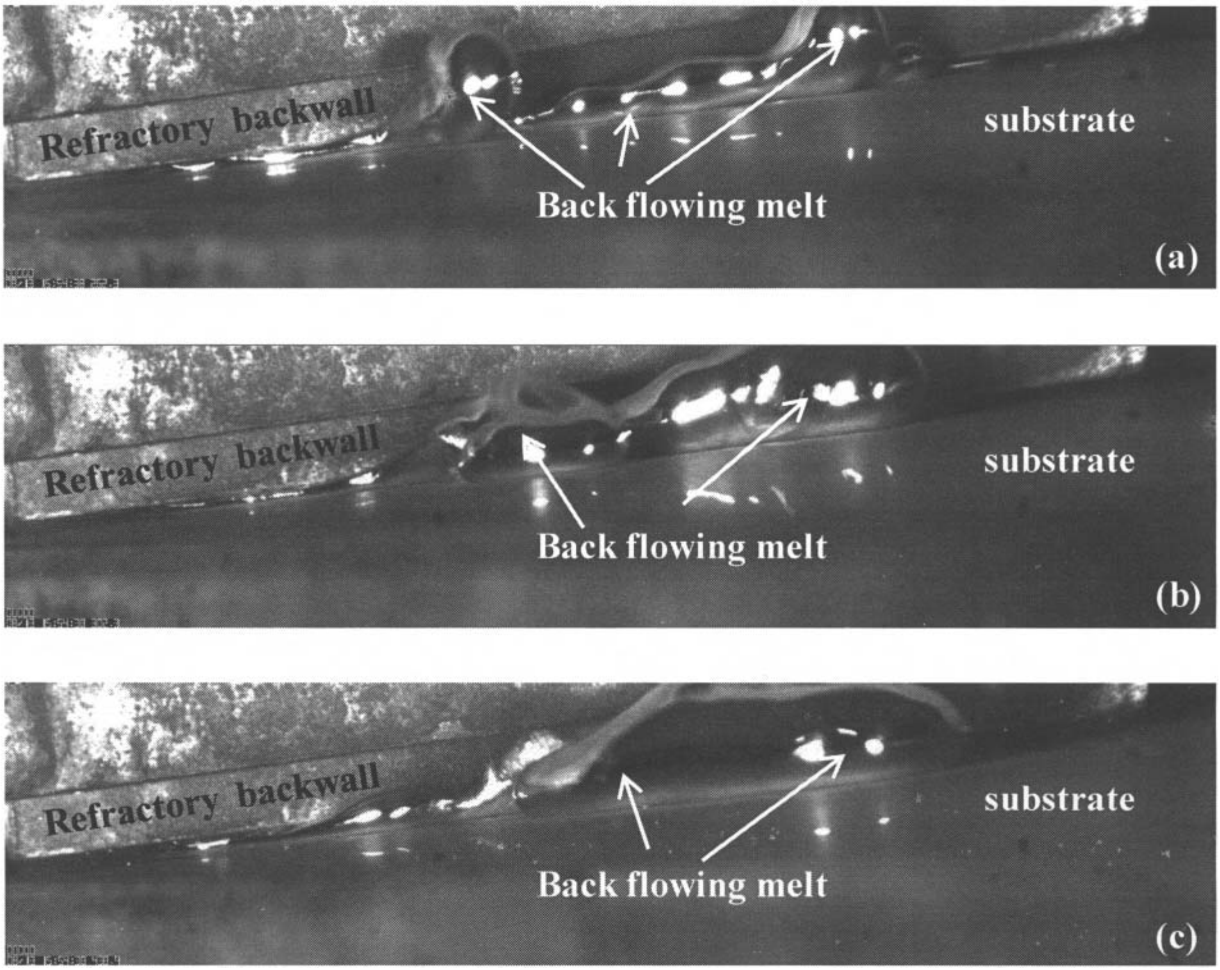

Figure 11. Photo of air/aluminum melt interface near the front of the refractory backwall, taken at different moments after the start of casting. The backwall/belt gap was 1.1~1.2mm, and the substrate speed was 0.4m/s. (a) at 0.06s; (b) at 0.10s; (c)at 0.25s.