Mathematical Modeling and Microstructure Analysis of Al–Mg–Sc–Zr Alloy Strips Produced by Horizontal Single Belt Casting (HSBC)

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Horizontal Single Belt Casting (HSBC) is a near net shape strip casting technology that will probably gain significant prominence in the coming years. Fluid mechanics and associated heat and mass transfer are important aspects of any continuous casting process, and the HSBC process is no exception.

In this study, mathematical models have been developed, using ANSYS FLUENT 14, to assess various aspects of the HSBC process for the Al–Mg–Sc–Zr system. Specific emphasis is placed on a) the effects of substrate surface properties on strip quality, b) liquid metal-air two-phase interactions and meniscus behavior, c) heat fluxes between the metal and substrate, and d) solidification behavior during strip casting. These predictions are validated against experimental casting results. A 5000 series Al–Mg alloy, with added Sc and Zr, shows exceptional potential as a structural material for aerospace and transportation applications. It is also a suitable material to be produced via the HSBC process. Optical microscopy, SEM and EBSD analyses were conducted to compare the potential advantages of casting this alloy via the HSBC process versus conventionally produced Direct Chill Casting.

KEY WORDS: strip casting; Horizontal Single-Belt Casting (HSBC); modeling; Al–Mg–Sc–Zr alloys.

1. Introduction

Near Net Shape Casting (NNSC) refers to processes in which molten metals can be cast into products with dimensions close to the final products, thereby minimizing the downstream size-reductions required to produce sheet products. Driven by its advantages in terms of reductions in cost, energy and pollution over conventional casting processes, NNSC is one of the most promising areas for casting research in process metallurgy. The Horizontal Single-Belt Casting (HSBC) process is one such NNSC process. Independently conceived by Herbertson and Guthrie,1) and Reichelt, Scheulen, Schwerdtfeger, Voss-Spilker and Feuerstakc2) in 1990, it involves pouring molten metal, isokinetically, onto a horizontal, water-cooled, metallic conveyor belt, where the melt solidifies into thin strips, several mm thick and 1–2 metre(s) wide.3) Due to the thin as-cast strip thickness and relatively high casting speeds (~1 m/s), high cooling rates can be achieved during the HSBC process. These high solidification rates not only reduce as-cast grain sizes, but also significantly reduces the degree of elemental segregation effects within the solidifying metal, leading to improved mechanical properties.4,5) Various transport phenomena and solidification behavior, for both ferrous and non-ferrous alloys, have been extensively investigated by the researchers at the MMPC.6)

The application of Computational Fluid Dynamics (CFD) has proven to be extremely useful in modeling the HSBC process. Numerical analyses were conducted, emphasizing aspects such as heat transfer,7,8) casting substrate characteristics,9) general flow and solidification,10–12) and electromagnetic behaviour,13) pertaining to the HSBC process.

The medium-strength 5000-series aluminum alloys containing magnesium exhibit high ductility, good corrosion resistance, as well as good weldability. The further additions of Sc and Zr to these alloys substantially improve the strength, workability and high temperature resistance of these alloys.14–17) As such, Al–Mg–Sc–Zr based alloys have become important candidates for aerospace applications.18)

In the Al–Mg–Sc–Zr system, Mg is mainly present in the dissolved state, generating solution strengthening, whereas Sc and Zr additions provide strengthening through the formation of Al3(Sc,Zr) precipitates, and by grain refinement. The high mechanical strength of this system results mostly from Orowan Strengthening via dislocation pinning.14–19) In addition to this, it is reported that Al3(Sc,Zr) precipitates also delay recrystallization during hot working, which allows alloys based on the Al–Mg–Sc–Zr system to maintain their strength at higher temperatures versus equivalent alloys without Sc/Zr.19) In most of the studies, gravity casting has been used as the processing route, followed by heat treatment, since the main focus was precipitation hardening. However, Kendig et al. reported that the influence of grain boundary strengthening on Al–6Mg–2Sc–1Zr (wt.%) alloy’s mechanical strength was higher than both the effects of precipitation and solution strengthening.20) In the present study, mathematical models, developed using ANSYS FLUENT 14, were used to predict and simulate various transport phenomena associated with the production of Al–Mg–Sc–Zr
alloy strips using the HSBC process. Specific emphasis was placed on the modeling of substrate roughness, liquid metal-air interface/meniscus behavior, and interfacial heat fluxes between the metal and the water-cooled, or mold chill substrates. Solidification behavior during strip casting has also been modeled from first principles. Transient simulations were performed to monitor the process, the Volume of Fluid (VOF) method being used for the tracking of the free surface. The reliability and robustness of the present mathematical model was tested against experimental casting results performed on the HSBC simulator at the MMPC.

A microstructural analysis and mechanical tests were also performed on the Al–Mg–Sc–Zr alloy strips produced by the HSBC process, so as to evaluate the suitability of the HSBC process for the production of these alloys, and to investigate its advantages over conventionally produced as-cast Al–Mg–Sc–Zr alloy strips.

2. Mathematical Modeling Theory

The mathematical model developed attempts to simulate four important aspects of the HSBC process, shown in Fig. 1. These four aspects are: 1) modeling a two-phase interface using the VOF model, for the transient tracking of the melt/air interface. 2) modeling turbulence in the fluid phases (especially the melt), using the standard \( k-\omega \) model, to investigate its possible influence on heat transfer and meniscus behavior. 3) study of the effect of the roughness of the substrate surface on the flow of the melt, using a modified Law-of-the-Wall and Nikuradše’s Equivalent Sand-Grain Roughness method. 4) prediction of as-cast strip thickness, and melt/substrate interfacial heat fluxes using a modified energy equation to incorporate solidification and a ‘mushy-zone’.

2.1. The Volume of Fluid (VOF) Model

The Volume of Fluid (VOF) model is commonly used in multiphase modeling of two or more immiscible fluids (phases \( q \) and \( p \)), where the volume fraction of each fluid can be tracked throughout the domain by solving one set of momentum equations.\(^{21}\) The volume fraction continuity equation is shown below, where \( \alpha_q \) represents the volume fraction of the phase \( q \) in a cell, \( m_{pq} \) and \( m_{pq}^* \) are mass transfers from phase \( p \) to \( q \) and phase \( q \) to \( p \) respectively, while \( \rho \) represents density of each phase. The source term, \( S_{aq} \), is zero in this application, since there is no creation or destruction of any phase and the two phases are immiscible.\(^{21}\)

\[
\frac{1}{\rho_q} \left( \frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \mathbf{v}_q) \right) = S_{aq} + \left( m_{pq}^* - m_{qp}^* \right) \quad \ldots (1)
\]

The equation states that the transient change in volume of phase \( q \) in a given cell and the volumetric flow of phase \( q \) into the cell, should be equal to the sum of a source term for the production of phase \( q \) (zero) and the volume transfer between phases \( q \) and \( p \). In this case this is also zero, since the phases are treated as immiscible, non-interpenetrating and insoluble in each other. The volume fraction of the individual phases in a cell can be calculated using the constraint shown at the end of Eq. (1), which states that the sum of all phases (in this case, only \( p \) and \( q \)) in a given cell is 1.

Explicit time discretization is used to solve the volume fraction equation for this transient model. This equation is shown below. \( \alpha_q \) and \( \alpha_q^* \) are the computed face value of the volume fraction of phase \( q \). \( V \) is the cell volume and \( U_q \) is the volumetric flow through a specific face, based on normal velocity.\(^{21}\)

\[
\frac{\alpha_q^{n+1} - \alpha_q^n}{\Delta t} + \sum_j \left( \rho_j U_j \alpha_q^n \right) = \left[ \left( m_{pq} - m_{qp} \right) + S_{aq} \right] V
\]

This equation states that the sum of the volumetric change of phase \( q \) over one timestep of size \( \Delta t \), and the sum of the volumetric flow of phase \( q \) across all the faces of the cell, is equal to the sum of the source term and the volume transfer between the phase \( q \) and all phases \( p \). In this case, it is once again equal to zero, because the air is treated as being insoluble in the melt.

2.2. Standard \( k-\omega \) Turbulence Model

In order to model the turbulence within the molten metal flowing from the tundish onto the moving substrate, the turbulence model chosen for adoption was the standard \( k-\omega \) model rather than the standard \( k-\epsilon \) model. This model was developed by D. C. Wilcox, based on empirical data. It is applicable to many cases of wall-bounded and free shear flows.\(^{21,22}\) The transport Eq. (3) for the turbulent kinetic energy, \( k \), is given below, where \( k \) represents the local kinetic energy of turbulence per unit mass of fluid, and models the turbulent fluctuations within the flow. The unit of measurement of \( k \) is \( \text{m}^2/\text{s}^2 \). The specific turbulence dissipation rate, \( \alpha_\epsilon \) in Eq. (4), represents the rate at which \( k \) is converted into thermal internal energy per unit time and volume. \( \alpha_\epsilon \) is defined in the present model as \( \alpha_\epsilon = \frac{\epsilon}{k \beta} \), where \( \epsilon \) represents the turbulence dissipation used in standard \( k-\epsilon \) equation. The units of \( \alpha_\epsilon \) are 1/s.
\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left( \Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k + S_k \quad \ldots \quad (3)
\]

\[
\frac{\partial}{\partial t} (\rho \omega) + \frac{\partial}{\partial x_j} (\rho \omega u_j) = \frac{\partial}{\partial x_j} \left( \Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + S_\omega \quad \ldots \quad (4)
\]

Γ terms represent an effective diffusivity. The G terms are the turbulence production terms. Y terms represent the dissipation due to turbulence. S terms represent the source terms for k and ω.

The effective diffusivities are calculated by the following equations. The σ terms represent turbulent Prandtl numbers.

\[
\Gamma_k = \mu + \frac{\mu_\tau}{\sigma_k}, \quad \Gamma_\omega = \mu + \frac{\mu_\tau}{\sigma_\omega} \quad \ldots \quad (5)
\]

\[
\mu_\tau = \alpha^* \frac{\rho k}{\omega} \quad \ldots \quad (6)
\]

The dimensionless coefficient α* dampens μ, which gives a low-Reynolds-number correction near wall boundaries.21) It is calculated by the following equation, in which Re_c = (ρk)/(μω) and \( \alpha_0 = \beta/3 = 0.024 \).

\[
\alpha^* = \alpha^*_s \left( \frac{\alpha_s' + \text{Re}_c/\text{Re}_k}{1 + \text{Re}_c/\text{Re}_k} \right) \quad \ldots \quad (7)
\]

The constants used in the standard k-ω model are: \( \alpha_s' = 1, \alpha_s = 0.52, \alpha_0 = 1/9, \beta_s = 0.09, \beta = 0.072, \text{Re}_k = 8, \text{Re}_c = 6, \text{Re}_m = 2.95, \text{M}_0 = 0.25, \zeta^* = 1.5, \alpha_1 = \alpha_s = 2.0. \)

2.3. Roughness Model

To model the flow of liquid metal over the moving chill substrate, one can either assume that this is totally smooth, or totally rough. In our previous works, we have shown how metal solidification is initiated on the ‘peaks’ of the substrate, and spreads across the aluminum melt surface ‘sitting’ on these ‘peaks’, until the whole surface in contact with this rough surface, is frozen. We have demonstrated that this occurs within the first 20 milliseconds of contact, and that solidification then proceeds normal to the direction of heat extraction. For both the simulator, and the pilot-scale ISIJ caster, shown in Fig. 1, this is vertically upwards into the over-laying melt. While the liquid metal does not ‘wet’ the substrate, owing to the interfacial gas films separating it from the substrate, we can assume either a fully smooth, or a fully rough, situation. Figure 2 illustrates the latter situation, using the ‘equivalent sand-grain method’.21)

The Law of the Wall, proposed by van Karmen in 1930, states that the mean velocity of a fluid in turbulent flow at a specific point is proportional to the logarithm of the distance between said point and the no-slip boundary of the fluid, i.e., the ‘wall’.21) The roughness of the wall will add an additional term to this proportionality equation that reduces the mean velocity of the fluid near the wall. This additional term depends heavily on the characteristic and size of the roughness.24,25)

In the current model, available in Ansys FLUENT, a close-packed monolayer of spheres (of diameter \( K_s \)) can be used to cover the substrate surface uniformly, so as to mimic the effect of a real, rough, surface, allowing for easier determination of average roughness height and calculations. The conversion from real roughness height (\( K \)) to equivalent roughness height (\( K_s \)) varies significantly, depending on the type of roughness (wire-mesh, corrugated, wavy, etc.). For technical roughness, such as the roughened Cu substrate used in this study, it is assumed that \( K \approx K_s. \)

Note that when using equivalent-sand-roughness, the blockage effect is about 50% of the sphere’s diameter (only the top half of the sphere ‘blocks’ the flow of the fluid), which in turn means that the wall is physically displaced (upwards in Fig. 2) by \( K_s/2 \). This wall shift is taken into account in the numerical model to give the correct displacement due to the surface roughness.21)

2.4. Solidification Model

The effect of alloy solidification, including the effect of the ‘mushy zone’ between the liquidus and solidus region, on fluid flow, was also taken into account in the present model. This modifies the energy equation such that the overall enthalpy includes both sensible heat and latent heat of the material (L). The effect of a ‘mushy zone’ was accounted for using a liquid fraction parameter, \( \beta \), defined as follows:

\[
\beta = \frac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}} \quad \ldots \quad (8)
\]

The modified energy equation becomes:

\[
\frac{\partial}{\partial t} (\rho H) + \nabla \cdot (\rho \dot{\mathbf{v}} H) = \nabla \cdot (k \nabla T) + S \quad \ldots \quad (9)
\]

\( S \) is the source term and \( H \) is the enthalpy, defined in the following equation:

\[
H = h_{\text{fus}} + \int_{T_{\text{ref}}}^T c_p dT + \beta L \quad \ldots \quad (10)
\]

In terms of momentum and turbulence, the partially solidified region, or ‘mushy zone’, is treated as a porous media. The porosity of a cell is proportional to the liquid fraction in the region, such that the porosity of a fully solidified region becomes zero and the solidified shell moves forward at the substrate speed, all relative velocities are thus extinguished.21) Within the mushy area, Darcian-type flow is assumed.

This introduces sink terms to the momentum and turbulence equation, as well as a mushy zone constant \( A_{\text{mush}} \). The momentum sink term is shown below:

\[
S = \left( \frac{1 - \beta}{\beta^3 + \varepsilon} \right) A_{\text{mush}} \left( \dot{\mathbf{v}} - \dot{\mathbf{v}}_p \right) \quad \ldots \quad (11)
\]

where \( \varepsilon \) represents a very small number (0.001), introduced to avoid division by zero. \( \dot{\mathbf{v}}_p \) is the solid pull velocity, which is the velocity at which the solidified strip will move at. This is set to be the same as the substrate moving speed in the
model.

The turbulence sink term for the standard $k-\omega$ turbulence model is shown below in Eq. (12), note that the $\omega$ here represents the specific dissipation rate from the turbulence model.

$$S = \frac{(1-\beta)^2}{(\beta + \epsilon)^3} A_{mush}\omega \quad \ldots \ldots \ldots \ldots \ldots (12)$$

3. Setup of the Numerical Model and its Parameters

A two-dimensional, double precision system geometry and mesh was created using GAMBIT 2.4.6, and exported as a case file compatible with ANSYS FLUENT 14.0. Quadrilateral cells were used throughout the computational domain for meshing. The largest cell size was ~600 $\mu$m and the smallest cell sizes, near the meniscus and impact region, were ~13 $\mu$m. The purpose of this was to obtain a smooth meniscus profile and velocity field. The mesh was refined and readjusted, until a grid independent solution was obtained. The model, in total, had approximately 78,000 cells. The mesh, as well as the initialization for the transient model, is shown in Fig. 3.

In this model, liquid aluminum was used as the melt. The physical properties of the fluids used in the model are given in Table 1. The operating parameters and some of the assumptions of the model are shown in Table 2. The transient solution was calculated using a Non-Iterative Time Advancement (NITA) scheme, with a variable time step size, between $1 \times 10^{-8}$ s to $5 \times 10^{-6}$ s, so as to maintain a global Courant number of 0.10. The convergence criteria of $1 \times 10^{-4}$ were used for all equations at each time step. The Fractional Step Method (FSM) was used for pressure-velocity coupling, and 2nd order upwind schemes were used for momentum and energy spatial discretization. For the modeling of turbulence using the $k-\omega$ model, the low-Reynolds number correction was activated for better near-wall flow treatment.

The dynamic contact angle data between molten aluminum and the copper substrate in air used in the numerical model was taken from results of previous experiments performed at the MMPC. The experiment involved plunging a model was taken from results of previous experiments per-

The effect of varying substrate speed was also evaluated. To model the heat extraction from the melt by the copper chill mould/substrate, the model assumed one-dimensional heat conduction through the ½ inch thick copper substrate in the vertical direction. The boundary condition for the conduction calculation was that the bottom side of the Cu substrate remains at room temperature (25°C). This assumption is reasonable considering that the Cu substrate has much higher thermal conductivity, and is much thicker than the as-

Table 1. Physical properties of the fluids used in the model.\(^{27,28}\)

<table>
<thead>
<tr>
<th>Property, Nomenclature and Unit</th>
<th>Liquid Aluminum</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$ (kg/m(^3))</td>
<td>2.300</td>
<td>1.225</td>
</tr>
<tr>
<td>Specific Heat Capacity, $C_p$ (J/kg-K)</td>
<td>1177.17</td>
<td>1006.43</td>
</tr>
<tr>
<td>Thermal Conductivity, $k$ (W/m-K)</td>
<td>104</td>
<td>0.0242</td>
</tr>
<tr>
<td>Viscosity, $\mu$ (kg/m-s)</td>
<td>0.001338</td>
<td>1.7894 E-5</td>
</tr>
<tr>
<td>Molecular Weight (kg/kgmol)</td>
<td>26.98</td>
<td>28.966</td>
</tr>
<tr>
<td>Standard State Enthalpy (J/kgmol)</td>
<td>1.100493 E+7</td>
<td>0</td>
</tr>
<tr>
<td>Reference Temperature (K)</td>
<td>298.15</td>
<td>298.15</td>
</tr>
<tr>
<td>Initial Temperature (K)</td>
<td>953.15</td>
<td>300</td>
</tr>
<tr>
<td>Pure Solvent Melting Heat (J/kg)</td>
<td>387000</td>
<td>–</td>
</tr>
<tr>
<td>Solidus Temperature (K)</td>
<td>861.15</td>
<td>–</td>
</tr>
<tr>
<td>Liquidus Temperature (K)</td>
<td>923.15</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 2. Operating parameters and assumptions used in the models.\(^{25}\)

<table>
<thead>
<tr>
<th>Operating Parameter</th>
<th>Value/Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface tension coefficient of liquid aluminium in air</td>
<td>0.914 N/m</td>
</tr>
<tr>
<td>Contact angle between liquid aluminium and alumina refractory</td>
<td>135°</td>
</tr>
<tr>
<td>Dynamic contact angle between liquid aluminium and copper substrate</td>
<td>105°–140°</td>
</tr>
<tr>
<td>Heat transfer across refractory</td>
<td>0 (adiabatic)</td>
</tr>
<tr>
<td>Copper substrate movement speed</td>
<td>0.8 m/s</td>
</tr>
<tr>
<td>Nozzle size</td>
<td>3 mm</td>
</tr>
<tr>
<td>Nozzle inlet flow velocity</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Mushy zone constant</td>
<td>100000</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>Standard k-\omega</td>
</tr>
<tr>
<td>Substrate surface roughness (equivalent-sand-grain roughness height)</td>
<td>4.5 $\mu$m</td>
</tr>
</tbody>
</table>

cast aluminium strip. In this manner, the interfacial heat fluxes between the melt and the substrate could be predicted using the model.

The completed numerical model took into account the surface roughness of the substrate for fluid flow predictions. The roughness conditions of the model were set at $K_s = 4.5 \mu$m (equivalent sand-grain roughness), equivalent to that measured by 3D profilometry from the Cu substrate used in the experiment. Solidification was also incorporated into the model; both in terms of energy transfer (latent heat, etc.), and in terms of fluid flow (damping of turbulence, etc.). The effect of varying substrate speed was also evaluated. However, more complex three-phase effects, such as air entrainment within the crevices of the substrate surface, were not considered. The roughened substrate was assumed to be in perfect contact with the melt for these flow calculations.
3.1. Transient Interfacial Heat Fluxes

In order to take into account the effect of gas entrainment in the surface crevices of the substrate on interfacial heat transfer, the substrate was discretized into 20 different segments and each given a thermal resistance. The predicted interfacial heat fluxes are then compared to experimentally measured heat fluxes and used to optimize the thermal resistance profile across the substrate in an iterative manner. Two major assumptions made in the models are 1) the ½ inch thick substrate conducts heat one-dimensionally in the vertical direction with constant base temperature, and 2) the model is a 2D simplification of a 3D process. Phenomena such as the effects of strip width and cross-flows are not considered.

The mathematical model attempted to predict the interfacial heat flux between liquid melt and the copper substrate. Physical properties of the four phases (molten melt, surrounding air, solidified shell and copper substrate) and operating parameters of the process (substrate speed, melt inflow rate, substrate roughness, etc.) were used to model the process, using the various methods and assumptions.

4. Experimental Procedure

4.1. Model Validation

In order to validate the predictions of the numerical model, casting experiments of Al–Mg–Sc–Zr alloy strips were performed on the HSBC simulator. The alloy had a nominal composition of Al–4Mg–0.6Sc–0.12Zr (wt.%). It was prepared using an induction furnace from pure Al, pure Mg, and master alloys of Al–2Sc (wt%) and Al–10Zr (wt.%).

The design of the metal delivery system of the simulator is shown in Fig. 1, and is similar to that used for the pilot-scale caster production tests for this alloy. The HSBC simulator consists of a moving sandblasted copper (99.9%+ pure) chill substrate that is driven by a compression spring system to travel at a specific velocity laterally, under the stationary refractory-lined tundish. The delivery nozzle at the base of the tundish opens automatically as the substrate begins to move and allows approximately 0.5 kg of melt to deposit along its length, and to subsequently solidify above, the copper substrate. The copper substrate has integrated T-type thermocouples embedded within, so as to record transient temperature changes of the substrate during casting. The temperature data from the thermocouples are logged using a computer using DASYLab data acquisition software at 0.02 second intervals.

A high-speed video camera, and appropriate lighting, was placed on the spring side of the simulator to record the appearance and movements of the meniscus at the melt-air-substrate triple point during casting, at 300 a rate of frames/second. The HSBC simulator and high-speed video camera setup is shown in Fig. 4.

4.2. Pilot-Scale Casting for Microanalysis

The same Al–4Mg–0.6Sc–0.12Zr (wt.%) was also cast on the pilot-scale HSBC caster at the MMPC. The pilot-scale caster is much larger than the simulator, but functions on the same principle. They differ in a few aspects: instead of a moving Cu substrate, the pilot-scale caster uses a 2.6 m long water-cooled endless steel belt. The steel belt is sandblasted, as well, but used a layer of graphite coating on the surface to moderate interfacial gas expansion effects on the bottom surface quality of the long lengths of strips produced.

Approximately 130 kg of the Al–Mg–Sc–Zr alloy were melted in an induction furnace. The furnace was then moved to the casting station where the melt was displaced upwards and into the launder of a low head metal delivery system using a downward-pressing piston. Then, the melt was metered through a slot nozzle, allowing the molten alloy to flow onto the steel belt substrate. Melt temperature during casting was maintained at 694–695°C. The melt then solidified into a continuous, thin sheet, 70–100 mm wide, and 5–7 mm thick. Three batches of strips were produced. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) tests were then performed on the strip to determine its exact composition. The composition of the strips are shown in Table 3.

The as-cast strips were then cut into appropriate sizes for Optical Microscopy (OM), and Scanning Electron Microscopy (SEM). The specimens were ground and polished, down to a 1 μm diamond paste in an alcohol-based lubricating fluid. Kellers solution (5 ml nitric acid, 3 ml hydrochloric acid, 2 ml hydrofluoric acid and 190 ml distilled water) was used to etch the sample for OM analysis. For EBSD analysis, samples were further polished down to 0.04 μm, using a vibratory polisher for up to 6 hours. SEM analysis was conducted using a Hitachi S-3000N VP-SEM and a...
Philips XL-30 Field Emission-SEM (FE-SEM) at 20 kV. EBSD data was collected and analyzed using TSL software with 0.5 \( \mu m \) intervals. Additionally, surface roughness profiles of Al–Mg–Sc–Zr strip casts were measured using a NANOVEA 3D profilometer, while Vickers hardness (HV) values were measured using a 5 kg load.

5. Results and Discussion

5.1. Steady-state Air/Melt Interface Behavior and Flow Field

Figure 6(a) shows the steady state phase distributions and

![Figure 6(a) showing steady state phase distributions and flow field predictions.](image)

Fig. 6. a) Steady-state meniscus and flow field predictions of the models. The location of the menisci and its stability agrees with the experimental result shown in Fig. 7. b) Steady-state melt/solidified shell thickness and velocity fields, 80 mm downstream from the nozzle, predicted by the numerical model for a substrate speed of 0.8 m/s. c) Steady-state liquid fraction distribution. The Blue Zone is completely solidified shell, the Red Zone is 100% fluid (melt and air), while the colours in between represent the mushy zone.

![Figure 6(b)](image)

![Figure 6(c)](image)

![Figure 6(c)](image)

Fig. 8. Steady-state melt/solidified shell profiles predicted by different models under the substrate speed of 0.8 m/s. Steady-state final strip thickness is ~ 3.75 mm. Note the predicted hydraulic jump right after melt impinges onto the substrate.

![Figure 14](image)

Fig. 14. SEM-EDS mapping across the grain boundary, showing polygonal phases found in the as-cast strip, for Al, Mg, Sc and Z. Also showing the locations where EDS point analyses were conducted. Note that the Al content in the region of the grain-boundary phase is slightly less than the matrix.

![Figure 16](image)

Fig. 16. 3D profilometry results, a) strip bottom surface topography and b) roughness analysis and c) strip top surface topography and (d) roughness analysis.
fluid velocity field near the impact region, as predicted by the numerical model, where the shape and position of the meniscus can be clearly seen. The predicted shapes of the meniscus agree qualitatively with the experimental results. The shape of the meniscus predicted is also in good agreement with mathematical modeling results for the HSBC process available in the literature.\textsuperscript{11,30} The shape of the melt/air interface meniscus is very important for the HSBC process. The position and stability of the back-wall meniscus could have major effects on the entrapment of air in the crevices on the rough substrate.

The mathematical model predicted that a stable meniscus would be formed in the 0.7 mm gap between the back wall and the substrate (the back-wall meniscus). This agrees qualitatively with experimental results from previous work,\textsuperscript{11,30} which showed that no back flow (the flow of melt against the movement of the substrate, under the gap, thereby forming an upstream unstable meniscus) would occur under the specified operating parameters, that is, for a substrate speed $\geq 0.4$ m/s, for a gap height of $\leq 0.7$ mm.\textsuperscript{11,30} Figure 7 shows the photograph, taken by the high-speed video camera, during casting on the HSBC simulator, illustrating the presence of a steady state air/melt interface.

### 5.2. Melt Velocity Field and Strip Thickness Prediction

Figure 8 shows the predicted steady-state melt/solidified shell profile along the substrate, as well as the predicted strip thicknesses. Figure 6(b) shows the detailed phase distribution and velocity fields near the end of the computational domain ($x = 80$ mm).

With the incorporation of solidification in the model, the melt flow becomes even slower as the flow is dampened by the ‘mushy zone’. We predict this further decelerates the melt, making its velocity even closer to that of the substrate, thereby further increasing the strip thickness predicted. Figure 6(c) shows the liquid fraction/degree of solidification of the melt predicted by the model, the same region as in Fig. 6(b). As can be seen, the melt in the fully solidified (blue) region moves synchronously with the substrate at the given substrate speed (as a boundary condition), while the free-stream velocity of the melt is dampened by the ‘mushy zone’. The experimentally cast strip, for a substrate speed of 0.8 m/s and a nozzle size of 3 mm, had an experimentally measured thickness of 3.87 ($\pm$ 0.45) mm at its mid-length-section, where it can be assumed to be at steady state. Moreover, it was observed during experiments that the melt does come into contact with the bottom of the front refractory, validating the predicted hydraulic jump. These observations seem to confirm the general validity and application of the mathematical models being developed.

### 5.3. Transient Interfacial Heat Fluxes across the Melt/Substrate Interface

In terms of interfacial heat fluxes, the mathematical models assumed imperfect contact between liquid metal and the substrate, with variable interfacial thermal resistance. Predicted interfacial heat fluxes were also verified quantitatively against experimental results for a deep textured copper substrate with very smooth upper surfaces. The fluxes were determined experimentally using temperature-time data derived from the substrate-integrated thermocouples embedded in the HSBC simulator, and calculated using the IHCP (Inverse Heat Conduction Problem) technique.

As noted, the experimental results that were used to validate the model predictions were derived from casting aluminum alloys on a macroscopically textured copper substrate; the latter was designed to reduce the effect of gas entrapment and expansion of air pocket formation at the melt/substrate interface.\textsuperscript{11} The gases entrapped between the melt and the substrate form tiny air pockets on the interface. As the air is heated up and expands, these air pockets coalesce into larger air gaps, preventing good contact between the melt and the substrate, thereby causing the interfacial heat fluxes to decrease rapidly.

In order to account for this effect, a varying interfacial thermal resistance was added as a boundary condition across the melt-substrate interface in the model. The values of thermal resistance used were based on previous studies on heat transfer in strip casting processes.\textsuperscript{7} The model was then run until the transient simulation essentially reaches a steady state, at which point the transient interfacial heat fluxes predicted was compared to experimentally measured results. Through the iterative process adjusting the thermal resistance profile and repeating the solution, an optimized thermal resistance was obtained, as shown in Fig. 9. This optimized transient thermal resistance was verified against previous studies on the evolution of interfacial air gaps during strip casting, and was found to have a similar trend with the size of interfacial air layers at different contact times.\textsuperscript{32}

The experimentally determined heat flux results for the textured copper substrate are plotted as a function of melt contact time, together with the heat fluxes predicted by the model in Fig. 10. As seen, the magnitudes of heat fluxes predicted were in good agreement with our experimental results at the moment of melt contact with the substrate. The theoretical maximum interfacial heat fluxes, derived from the analytical solution of the process, were also plotted on the same axes.\textsuperscript{32}

As can be seen, the heat fluxes predicted were in very good agreement with the experimental results. The theoretical maximum heat fluxes was plotted on the same graph to illustrate the significance of the air gaps and other transport phenomena on interfacial heat transfer.

The biggest discrepancy between the measured and predicted heat fluxes lies in the position and magnitude of the peak heat flux. The model slightly underestimated the peak heat flux, more or less within the 10% experimental error of
the measured value. Furthermore, the measured peak heat flux appears at about 80 ms after initial melt contact while the model predicts that the peak heat flux appear at the first moment of melt contact with the substrate. This discrepancy can be attributed to the response time of the integrated thermocouples used to measure the heat fluxes, which inevitably delays the peak heat flux.

5.4. Thermodynamic Modeling

An estimation of the potential phases that could form in the as-cast strip was made, using the thermodynamic modeling software FactSage. An equilibrium pseudo-binary phase diagram was constructed for the strip’s actual composition (4 wt.% magnesium, 0.04 wt.% zirconium and 0–0.6 wt.% scandium, and the rest aluminium), as shown in Fig. 11.

According to the phase diagram, $\text{Al}_3(\text{Sc}_{1-x}\text{Zr}_x)$ phase should form from the liquid aluminum alloy, as primary phases. Moreover, the $\beta$-$\text{Al}_3\text{Mg}_2$ phase also forms from the $\alpha$-$\text{Al}$ matrix, at equilibrium. However, since the cooling rates of the HSBC process are higher than those in conventional casting (as high as 500 K/s in some cases), instead of forming large amounts of equilibrium $\beta$-$\text{Al}_3\text{Mg}_2$ phase, most of the magnesium in the alloy remains in the $\alpha$-$\text{Al}$ matrix. This is clearly demonstrated by comparing the micrographs shown in Figs. 12 (strip cast) and 13 (ingot-cast).

5.5. Microstructural Analysis

The optical microscopy images of the as-cast strips from 1) the pilot-scale HSBC caster and 2) the HSBC simulator are both shown in Figs. 12(a)–12(d). Micrographs of both strips show nearly identical microstructures, which validates the effectiveness of the simulator as a physical model. The presence of polygonal phases, 10–20 $\mu$m in size, is also noted. Based on the size and morphology of the polygonal phases, they are postulated to be primary phases formed while the alloy is in the liquid state. In addition to the polygonal phases, small amounts of grain boundary phases are present as well. No significant segregation of phases was observed across the thickness of the strip.

Energy Dispersive X-ray Spectroscopy (EDS) mapping was conducted using Scanning Electron Microscope (SEM) on the polygonal phases, as well as the grain boundary phases. The EDS results are shown in Fig. 14. It shows that the polygonal phases mainly consist of Zr and Sc, most of the Mg in the system remains in the $\alpha$-$\text{Al}$ matrix, and the small grain-boundary phase contains slightly more Mg than Al.

On the other hand, since the matrix is mostly aluminum, EDS-mapping cannot be used to determine the quantitative aluminum content profiles.
In order to observe the aluminum content of different phases, EDS point analyses were conducted on the polygonal phases and the matrix. The EDS point analyses results are shown in Table 4. The molecular formula determined for the primary polygonal phases can be estimated to be Al₃(Sc₁₋ₓ,Zrₓ), and is consistent with the literature.\(^{15,16,20}\) Magnesium is mainly present as a solute in the \(\alpha\)-Al matrix. There are also small amounts of magnesium in the grain boundary phases (presumably the \(\beta\)-Al₃Mg₂ phase).

Moreover, around 0.3 wt.% Sc remained dissolved in the \(\alpha\)-Al matrix after solidification. The solubility limit of Sc and Al is around 0.4 wt.% at 660°C, and drops to 0.07 wt.% at 500°C.\(^{20}\) This supersaturation of scandium in the aluminum matrix is due to the high cooling rates associated with the HSBC process, which are significantly higher than those needed to allow scandium to precipitate out of the aluminum matrix under equilibrium cooling.

EBSD analysis was conducted on the vertical cross-section near the centre of the strip, in the longitudinal direction. A schematic of the section used for EBSD analysis, and the grain structure obtained, are shown in Fig. 15. Average grain size measured by the linear intercept method was found to be 17 ± 4 \(\mu\)m. The morphology of the grains can be considered irregular and angular, with some degree of variance in grain sizes and shapes.

The measured grain size and morphology of as-cast HSBC strips is very different from those of ingot-cast alloys of similar composition, which report equiaxed grains of ~50 \(\mu\)m average size.\(^{34}\) This is evidently due to the significantly higher cooling rates of the HSBC process compared to ingot casting. The smaller grain size potentially offers better strength to the alloy by grain-boundary strengthening, in addition to the existing mechanisms of solution- and precipitation-strengthening.

Furthermore, in ingot-cast Al–Mg–Sc–Zr alloys of similar composition, considerable amounts of intergranular phases and/or solute-enriched interdendritic regions are present.\(^{16,34}\) Studies have shown that the formation of these Mg-rich intergranular/grain-boundary phases (\(\beta\)-Al₃Mg₂) causes a significant degree of micro-segregation that can only be removed by homogenizing the alloy at 450°C for 24 hours.\(^{34}\)

In strips produced by the HSBC process, the presence of these grain-boundary phases is minimized, and the EDS mapping analysis showed a very low degree of micro-segregation across the grain boundary. This is a significant advantage of the HSBC process, in that the high cooling rate allows the magnesium to remain within the matrix, rather than diffusing out to form grain-boundary phases. It also potentially eliminates the need for homogenization after casting.

### Table 4. Results of semi-quantitative EDS point analyses, performed at three different points.

<table>
<thead>
<tr>
<th>Location</th>
<th>Al</th>
<th>Sc</th>
<th>Mg</th>
<th>Zr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polygonal Phase (1)</td>
<td>64.9 wt.%</td>
<td>29.6 wt.%</td>
<td>–</td>
<td>6.4 wt.%</td>
</tr>
<tr>
<td>Polygonal Phase (2)</td>
<td>76.5 at.%</td>
<td>21.3 at.%</td>
<td>–</td>
<td>2.3 at.%</td>
</tr>
<tr>
<td>Polygonal Phase (3)</td>
<td>62.3 wt.%</td>
<td>30.6 wt.%</td>
<td>–</td>
<td>7.1 wt.%</td>
</tr>
<tr>
<td>Polygonal Phase (4)</td>
<td>75.3 at.%</td>
<td>22.2 at.%</td>
<td>–</td>
<td>2.6 at.%</td>
</tr>
<tr>
<td>Matrix (3)</td>
<td>94.9 wt.%</td>
<td>0.3 wt.%</td>
<td>4.7 wt.%</td>
<td>–</td>
</tr>
<tr>
<td>Matrix (4)</td>
<td>94.6 at.%</td>
<td>0.2 at.%</td>
<td>5.2 at.%</td>
<td>–</td>
</tr>
</tbody>
</table>

5.6. Surface Quality

During the pilot-scale casting experiments, a graphite coating was applied to the steel belt substrate in order to decrease the effects of interfacial gas pocket formation on the bottom surface quality of the strips. The beneficial effect of graphite coating on bottom surface quality of strips has been mentioned in an earlier study.\(^{33}\) The surface finishing quality of the as-cast strips produced by the HSBC simulator is nearly identical to that of the pilot-scale casts.

3D Laser Profilometry was performed on both surface of the strips, and the results are shown in Fig. 16. The quality of the bottom surfaces of strips was excellent. Small protruberances were visible; these are the points where first contact was established between the melt and the substrate. These in turn, lead to rapid heat transfer in those locations and to the initiation of nucleation of solid material. On the other hand, since the top surface solidified in open air, its roughness is higher. The appearance of the top and bottom surfaces of the as-cast strip is shown in Fig. 17.

5.7. Mechanical Properties

Tensile tests were conducted with 2–3 repetitions per sample, and 10 hardness measurements were performed.
Hardness values obtained for strip cast samples are in the range of 72–75 HV, as shown in Table 5, greater than the hardness (~65 HV) of conventional castings of similar composition (Al–4.11Mg–0.26Sc–0.14Zr). The higher hardness values observed in this study are a direct result of smaller grain sizes resulting from higher cooling rates. Moreover, the variation in hardness values is high, possibly due to the presence of randomly distributed, hard, primary Al₃(Sc₁₋ₓ,Zrx) phases.

### Table 5. Hardness test results of the as-cast Al–Mg–Sc–Zr strips produced by the HSBC process.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Hardness (HV)</th>
<th>Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71.5 ± 5.3</td>
<td>145.4 ± 6.8</td>
<td>240.2 ± 12.5</td>
<td>9.2 ± 1.5</td>
</tr>
<tr>
<td>2</td>
<td>72.4 ± 4.1</td>
<td>137.3 ± 3.6</td>
<td>251.2 ± 4.1</td>
<td>10.2 ± 0.4</td>
</tr>
<tr>
<td>3</td>
<td>74.1 ± 5.0</td>
<td>138.1 ± 2.4</td>
<td>246.6 ± 4.8</td>
<td>10.7 ± 0.1</td>
</tr>
</tbody>
</table>

6. Conclusions

The present research has made use of both physical and numerical models as well as microanalysis, to study the potential production and properties of Al–Mg–Sc–Zr alloy strips that would be produced using the HSBC process. The following conclusions can be drawn:

1. A first principles analysis using two-dimensional, transient mathematical models, incorporating different transport phenomena, has been developed for the HSBC process. Fluid flow, strip thickness, heat transfer analyses and solidification were used to evaluate the model, quantitatively and quantitatively, against experimental results and past literature. The predicted interfacial heat flux values matched the experimental results.

2. The physical model (HSBC simulator) is effective in simulating the pilot-scale HSBC process, in terms of replicating as-cast strips with nearly identical microstructure and surface finish.

3. The high interfacial heat fluxes of the HSBC process (an order of magnitude greater than in conventional continuous casting processes and ingot casting), and the more rapid solidification of the melt, allows for the production of a unique microstructure in the Al–Mg–Sc–Zr as-cast strips.

This unique microstructure consists of much finer (~17 μm), irregularly shaped grains with dispersed polygonal Al₃(Sc₁₋ₓ,Zrx) phases plus a very low degree of elemental microsegregation. This greatly contrasts with microstructures of ingot-cast alloys of similar composition, which consist of larger (~50 μm) equiaxed grains, plus a considerable degree of microsegregation.

4. Owing to its unique microstructure, as-cast Al–Sc–Mg–Zr strips produced by the HSBC process have up to 10 HV greater hardness than those produced via conventional casting techniques. Furthermore, ingot-cast alloys typically require up to 24 hr of homogenization at 450°C to attain a similar degree of elemental homogeneity (especially Mg) as those of as-cast strips produced by the HSBC process.

To conclude, the HSBC process would be capable of producing high-quality thin alloy strips at low cost, and represents an innovative and environmentally friendly approach to the production of sheet metal.

REFERENCES