Numerical simulation of DC casting of AZ31 magnesium slab at different casting speeds

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Abstract

A mathematical model of the direct chill (DC) casting process for AZ31 magnesium slab has been developed to predict the temperature evolution in the slab. The temperature fields at different casting speeds were compared and the optimum casting speed of 300 mm/s for 800 mm magnesium slab in the certain pouring temperature and cooling-water flow rate was obtained. The casting speed during the plant trial was consistent with the calculation.

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Keywords: AZ31 magnesium; Simulation; DC casting; Temperature field; Flow field

1. Introduction

Magnesium alloys have comprehensive properties which include low density, high specific strength and stiffness, excellent machinability, superior damping and magnetic shielding capacities. Therefore, they are particularly attractive in various fields, such as aviation and spacecraft, automobile, computer manufacturing, communication, optic instruments and so forth [1,2]. The direct chill (DC) casting process, which is used to produce the starting material for these applications, is receiving significantly more attention from the standpoint of process optimization [3]. But how to adjust the complex interaction among those casting parameters, especially for large ingot, is a challenge. The funds are wasted if only dependent on the plant trial without effective prediction. Hence, the casting speed, one of the most important parameters was studied during the DC casting of AZ31 ingot (308 mm × 810 mm) in the present work.

2. Calculation domain and governing equations

According to symmetrical characteristic, a quarter of the slab is used during this numerical simulation. The shape of the slab is approximated using the 3-D geometry as shown in Fig. 1.

Where L1 is 405 mm and L2 is 154 mm. In a 3-dimensional coordinate system, the governing partial differential equation describing the diffusive flow of heat for the symmetric domain is shown in Eq. (1).

\[ \nabla \cdot (- (k + k_T) \nabla T) = Q + q_s T - \rho C_p u \cdot \nabla T \]

(1)

where \( T \) is the temperature (K), \( k \) is the thermal conductivity (W/m K), and \( k_T \) is a function of the turbulent viscosity and the specific heat. \( \rho \) is the density (kg/m³), \( C_p \) is the specific heat (J/kg K), \( u \) is the velocity field and \( Q \) is the heat source. Mean while, \( q_s \), growth/absorption coefficient (W/m³/K), is assumed to be 0.

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3. Boundary conditions

The specific boundary conditions formulated in the model are as follows:
B1 is assumed as inlet boundary condition.

\[ T = T_{\text{in}} \]  \hspace{1cm} (2)

The temperature of the inlet is a constant that is just equal to the casting temperature and \( T_{\text{in}} \) is assumed to be 973 K.

B2 and B3 are assumed as insulation/symmetric boundary conditions.

It is assumed that there is no heat loss from the surface of the liquid in the mold and along the centerline of the slab, thus the equation describing the insulation/symmetric boundary conditions is given in Eq. (3)

\[-n \cdot (- (k + k_T) \nabla T) = 0\]  \hspace{1cm} (3)

B4, B5 and B6 are assumed as heat transfer boundary condition.

Eq. (4) describes the heat transfer condition including the primary and secondary cooling regions,

\[-n \cdot (- (k + k_T) \nabla T) = q_0 + h(T_{\text{surf}} - T_i)\]  \hspace{1cm} (4)

where \( h \) is an effective heat-transfer coefficient. It embodies heat-transfer processes including interface contact, radiation, conduction and heat transport to water. \( T_i \) is the surface temperature.

Table 1
Heat transfer coefficient at water chilling zone used in the analysis.

<table>
<thead>
<tr>
<th>Temperature range[°C]</th>
<th>Impingement zone Heat transfer coefficient [W/m² K]</th>
<th>Free falling zone Heat transfer coefficient [W/m² K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>290 &gt; T ≥ 140</td>
<td>160,000 + 500T</td>
<td>120,000 – 375T</td>
</tr>
<tr>
<td>140 &gt; T ≥ 100</td>
<td>−36,000 + 900T</td>
<td>−27,000 + 675T</td>
</tr>
<tr>
<td>100 &gt; T ≥ 25</td>
<td>−6000 + 600T</td>
<td>−4500 + 450T</td>
</tr>
</tbody>
</table>

Table 2
Thermophysical properties used in the model.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>AZ31</td>
<td>20</td>
<td>76.9</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>83.9</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>87.3</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>92.4</td>
<td>&gt;600</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>97.0</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>101.8</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>118.5</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>424</td>
<td>118.5</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>630</td>
<td>120</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>635</td>
<td>120</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>680</td>
<td>240</td>
<td>–</td>
</tr>
</tbody>
</table>
temperature of the slab, and $T_{\text{inf}}$ is the temperature of the mold and cooling water.

In the primary cooling region, the slab experiences a progressive reduction in heat transfer as the metal solidifies and a physical gap is formed between the slab and the mold due to contraction of the slab. In order to simulate the effect of the gap, the heat transfer coefficient of this region is evaluated using a faction of the liquid phase fraction according to Eq. (5):

$$h = h_{\text{contact}} \times B + h_{\text{air}} \times f_L (1 - B)$$  \hspace{1cm} (5)

where $h_{\text{contact}}$ is heat-transfer coefficient for contact conduction across the interface and $h_{\text{air}}$ is an equivalent heat transfer coefficient.
coefficient for conduction across the gap. \( h_{\text{contact}} \) and \( h_{\text{air}} \) are assumed to be 1500 W/m²K and 25 W/m²K, respectively.

The liquid phase fraction of the domain is estimated according to Eq. (6):

\[
B = \begin{cases} 
1, & T > T_m + \Delta T \\
\frac{T - T_m + \Delta T}{2\Delta T}, & (T_m - \Delta T) \leq T \leq (T_m + \Delta T) \\
0, & T < T_m - \Delta T
\end{cases}
\]  

(6)

where \( T_m \) is the temperature of the middle point of the solid–liquid range and \( \Delta T \) is the half width of the solid–liquid range which is assumed to be 33 K, half of the transition temperature.

In the secondary cooling region, the slab is in contact with water directly and is comprised of two regions of behavior: the impingement zone and the free falling zone [4]. The impingement zone encompasses a region of 50 mm based on the plant trial and defines the heat transfer from the slab to water where the cooling water has appreciable radial momentum. The free falling zone lies below the impingement zone and comprises a region where the cooling water has minimal radial momentum. The lower radial momentum in the case of the free falling zone results in a lower rate of heat transport. Hence, the differentiation within the secondary cooling regime is considered in the model [5]. The modified relationships for the base case casting conditions can be found in Table 1 [6].

In order to reflect the variation of the cooling water flow rates during the plant trials, the base case flow rate was multiplied by a scale factor according to the different flow rate case.

4. Casting parameters and thermo physical properties of AZ31

As known, the casting speed is ramped during the start-up phase and then is a fixed value during steady-state. In this model the casting speed is constant during the whole DC casting process. The casting speed is assumed to be controlled in the range from 20 mm/min to 70 mm/min. The cooling water flow rate is assumed to be 320 L/min, and the pour temperature is 973 K. The thermophysical properties of the slab are given in Table 2 including thermal conductivity, specific heat, and density.

5. Results and discussion

5.1. The feature of the temperature field and temperature gradient field

As shown in Fig. 2, the temperature distribution in the slab is calculated at the process condition in which the casting
temperature is 973 K and casting velocity is 35 mm/min. Six lines selected in the double symmetry faces are shown graphically in Fig. 2. Because of the direct contact between the slab and the spray water, the maximum value of temperature gradient is achieved on the surface when the slab is pulled out of the mold, as shown in Fig. 3. The temperature variation along the distance from the center of the slab is shown in Fig. 4. The temperature drops from the center to the surface and the rate in the thickness direction is faster than that in the width direction especially in the plane even with the bottom of the mold.

5.2. The temperature field and flow field at different casting speeds

The thermal model was also used to predict the temperature distribution in the slab during the DC casting process at different casting speeds. Fig. 5 shows the isothermal of the temperature at different casting speeds. The solidification temperature of AZ31 is 839 K. As shown in Fig. 5, it moves downward with a higher speed of casting. The melt on the surface away from the inlet has solidified when the casting velocity is below 30 mm/min and the casting is compelled to stop, owing to the break of melt supplement. With the increase of the cast velocity, the solid–liquid interface gradually approaches to the bottom of the mold. High speed should be avoided for the breakout accidents.

As shown in Fig. 1, in order to determine the velocity, two lines, L1 and L2, are selected in the contact area with the mold. Fig. 6 shows the variation of the distance between the solid–liquid paint and the mold bottom of the lines. With the casting velocity increasing from 20 mm/min to 30 mm/min, the position of solidified shell along the L2 rapidly falls. Solidified shell on L2 becomes more nearer to the inlet drops with the increasing of the velocity of casting accordingly and it is in sensitive when the velocity is higher than 30 mm/min. Along L1, the position of solidified shell falls rapidly as the velocity increasing from 30 mm/min to 35 mm/min and the change becomes gradually slowly above 35 mm/min.

The casting velocity should not be below 30 mm/min to make sure the edge of the slab can be filled by the melt. The value of the temperature gradient at point C increases with the increasing of casting velocity in Fig. 7. To avoid the crack, the casting velocity should be as low as possible, while the hold-core is prevented. It is obvious that the appropriate casting velocity range selected in the production of the 300 × 800 mm slab of AZ31 magnesium is 30 mm/min–35 mm/min. The result corresponds to the data obtained during the plant trial.

The melt moves around rapidly and slowly until the velocity is in the same direction in the process of the casting when it flows into the mold, as seen in Fig. 8. When the casting velocity is 25 mm/min, the melt on the surface in the mold has solidified and cannot reach the far end. The depth of the sump increases gradually with higher casting velocity.
6. Conclusions

Three-dimensional numerical model considering mass, momentum, and heat transport has been applied to simulate the process of casting 300 mm × 800 mm magnesium slab. The following conclusions have been drawn:

1. In the cross-section of the slab, the temperature gradient is larger in the length direction than that in the width direction.
2. The maximum value of temperature gradient appears when the slab first contact with cooling water.
3. The optimum casting velocity of the 300 mm × 800 mm magnesium slab is 30—35 mm/min.

Acknowledgments

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References