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Yucheng Zhang
University of Wollongong, yz997@uow.edu.au

X Cheng
University of Wollongong, xc979@uow.edu.au

D Wei
University of Wollongong, dwei@uow.edu.au

Xiaolin Wang
University of Wollongong, xiaolin@uow.edu.au

Z Jiang
University of Wollongong, jiang@uow.edu.au

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Study on Solidification during Twin-roll Casting of Magnesium Alloy

Y. Zhang*, X. Cheng, D. Wei, X. Wang, Z. Jiang

School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Wollongong / Australia

* Corresponding author: E-mail address: yz997@uow.edu.au / auga_34@yahoo.com.cn; Tel.: +61 2 4239 2325

Abstract

The process of vertical twin-roll casting including pouring, solidifying, rolling and cooling can be accomplished in a very short time. Some important process parameters in roll casting that are difficult to be obtained experimentally may be acquired by employing numerical simulation. In this paper, a numerical simulation has been conducted based on a 2D finite element model of vertical twin-roll strip casting coupling temperature, flow, and thermal stress. The influences of key process parameters including submerged nozzle depth and nozzle spray angle have been studied. The distribution of thermal stress was obtained and its effect on the cracks in the casting strip was discussed.

Keywords: Twin-roll casting, Magnesium alloy, Simulation, Thermal stress.

Introduction

Magnesium is the lightest structural metal. It owns many superior mechanical properties including low density, high specific strength, excellent die casting performance, and high shock resistance (Baker and Avedesian, 1999). Magnesium has extensive applications in electronics, automobile, military and aviation industries, which is the driving force behind the research. However, the application of magnesium is confined by existing moulding technology to a great extent. The semi-solid metal moulding which is the most perspective near-net-shape forming technology has been given more attention as it can produce high quality non-dendritic microstructure (Zhang et al., 2007).

As a modern short flow sheet manufacturing technology, twin-roll casting is significantly energy saving and can improve production process. The process that can yield intermediate and final products is based on fluent metal as a raw material and opposite twin-roll as a crystalliser (Fig. 1). The process of twin-roll casting including pouring, solidifying, rolling and cooling can be accomplished in a very short time. Therefore, it is inconvenient to study some complex physical phenomena experimentally. Furthermore, some important process parameters in twin-roll casting that are difficult to be obtained in experiments may be acquired by employing numerical simulation.

The twin-roll casting has been successfully applied in aluminium alloy, while the research on magnesium alloy is still in its incipient stage. According to the researches by Allen et al. (2001) and Ling (2004), the microstructure of magnesium strip in twin-roll casting process has some advantages, e.g. uniform distribution, less inclusions and better dispersion. The influence of some process parameters has been reported (Xie and Huang, 1999; Zhang et al., 2005, 2007; Miao et al., 2001, Santos et al., 2000; Guthrie and Tacares, 1998; Jiang et al, 2009). However, most previous simulations were carried out for studying the influence of a single parameter based on horizontal casting process, and few studies have focused on pouring temperature and nozzle angle spray.

In this paper, vertical twin-roll strip casting of Magnesium alloy AZ31 is investigated using numerical simulation. A 2D finite element model coupling temperature, flow, and thermal stress has been established and the influences of submerged nozzle depth and nozzle spray angle on the temperature-flow-thermal stress fields in the molten pool have been studied. The position of the cracks on real twin-roll casting strip can match the analysis of thermal stress. The results are useful for controlling the twin-roll casting process and improving the quality of products.

Figure 1. Illustration of vertical twin-roll casting, 1) nozzle, 2) fluent metal, 3) casting roll, 4) solidified metal, 5) casting strip.

FEM Simulation and Boundary Conditions

In twin-roll strip casting process, the molten pool in which a nozzle is submerged, is built up by two water-cooled rolls and side dam. The FEM model was established by employing ANSYS and is shown in Fig. 2. Only half molten pool was considered due to symmetry and the symmetry axis is the vertical dash line. The roll was represented by an arc. The bottom of the outlet was set as the original point. Quadrilateral mesh was used in the simulation and more than 40,000 elements were generated. The submerged nozzle and its surrounding meshes are enlarged and shown in the figure.

The Fluid, Structural and Thermal modules in ANSYS were employed in the simulation. Some important parameters are listed in Table 1. The initial temperature of nozzle is 1003k. The ambient radiant heat is 0.7W/ m²K to the surface of the fluent metal and strip. The load of press at the end of the strip is zero. The horizontal velocity is zero at the symmetry line and strip surface while the vertical
velocity of strip is 1 m/s. The rotation of roll is 76.5 rpm. The impact velocity of the fluent metal was adjusted for maintaining the casting speed when the nozzle spray angle was changed. The heat transfer coefficient of roll is 10000 W/m²°C. The casting material is magnesium alloy AZ31 and its properties are shown in Table 2 (Baker and Avedesian, 1999).

**Figure 2.** FEM model of twin-roll casting

**Table 1.** Basic casting process parameters in FEM simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of casting roll 2R (mm)</td>
<td>500</td>
</tr>
<tr>
<td>Casting speed Vc (m/s)</td>
<td>1</td>
</tr>
<tr>
<td>Thickness of casting strip 2h (mm)</td>
<td>2</td>
</tr>
<tr>
<td>Submerged nozzle depth (mm)</td>
<td>15, 20, 25</td>
</tr>
<tr>
<td>Nozzle spray angle (°)</td>
<td>-10, 15, 10</td>
</tr>
<tr>
<td>Initial temperatures (K)</td>
<td>1003</td>
</tr>
</tbody>
</table>

**Table 2.** Properties of AZ31

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>1.78</td>
</tr>
<tr>
<td>Liquidus temperature (°C)</td>
<td>635</td>
</tr>
<tr>
<td>Solidus temperature (°C)</td>
<td>575</td>
</tr>
<tr>
<td>Specific heat (J/kg°C)</td>
<td>1040</td>
</tr>
<tr>
<td>Thermal conductivity (W/m°C)</td>
<td>95</td>
</tr>
<tr>
<td>Latent heat (kJ/kg)</td>
<td>339</td>
</tr>
</tbody>
</table>

**Results and Discussion**

**Influence of submerged nozzle depth on temperature, flow and thermal stress.** The submergence nozzle depth is a very important parameter. It affects thermal transfer, flow field in the molten pool and the quality of final casting strip. In this simulation, the spray angle of the submergence nozzle is 10°, and the submerged nozzle depth is 15, 20 and 25 mm respectively. The temperature fields are shown in Fig. 3. The submergence nozzle depth has significant influence on thermal field. The temperature at the outlet increases with an increase of submergence nozzle depth. It reaches about 684 K when the submerged depth is 25 mm, followed by 20 mm then 15 mm. The temperatures at outlet are very close when the submerged depth is 20 and 25 mm while it is about 666 K, which is a bit low when the depth is 15 mm.

**Figure 3.** Effect of submerged nozzle depth on temperature field in molten pool of twin-roll casting. Nozzle spray angle: 10°. Submerged nozzle depth: (a) 15 mm, (b) 20 mm, and (c) 25 mm.

**Fig. 4** shows the temperature distributions along the symmetry line and at the interface between the roll and the fluent metal at different submergence nozzle depths. As shown in Fig. 4b and c, the temperature along the symmetry line basically keeps stable between 0.07 and 0.13 m because of the latent heat release in this range. However, when the submergence nozzle depth is 15 mm, the temperature fluctuates obviously when the distance is larger than
0.09mm, as shown in Fig. 4a. This may be because of the disorder flow resulted from the low submerged nozzle depth.

Outlet is the key area where the defects in casting strip may generate due to the complex stress distribution. The thermal stress field is shown in Fig. 5. It can be seen that the highest thermal stress emerges at the outlet, which can reach 4.69MPa.

![Figure 5. Thermal stress field when submerged nozzle depth is 15mm and spray angle is 10°.](image)

The effect of the submerged nozzle depth on the equivalent thermal stress at the outlet is shown in Fig. 6. The thermal stress increases with a decrease of submerged nozzle depth. The thermal stresses when the submerged nozzle depth is 20 or 25 mm are quite close while the thermal stress is significantly higher when submerged nozzle depth is 15 mm, which may result in the defects in the casting strip. Considering the distribution of both temperature and thermal stress, the submerged nozzle inserted depth of 20mm may be suitable for the vertical twin-roll casting of magnesium alloy strip.

![Figure 6. Effect of submerged nozzle depth on equivalent thermal stress at outlet. Nozzle spray angle is 10°.](image)

**Figure 4.** Relationship between submerged nozzle depth and temperature distribution. Nozzle spray angle: 10°. Submerged nozzle depth: (a) 15mm, (b) 20mm, and (c) 25mm.

The submerged nozzle depth also influences the temperature distribution at the interface between the roll and the fluent metal in the molten pool, as shown in Fig. 4. When the depth is 15 mm, the curve is smooth. But when the depth is 20 or 25 mm, fluctuation is exist (Fig. 4b and c). The distance between the nozzle and the interface is reduced with the increasing submerged depth. Therefore, the influence of disorder flow nearby the nozzle on the temperature distribution at the interface increases, which causes the fluctuation in the curves. This uneven temperature could affect the performance of the roll and the strip quality.
15°. When the rolls rotate, the semi-solid metal is in the backward slip zone and the fluent metal coming from the nozzle may be pushed up. The area of high temperature in which the fluent metal exists is narrow and always at the top even nozzle spray angle is -10°, as shown in Fig. 7c. 

![Image](image_url)

**Figure 8.** Effect of nozzle spray angle on equivalent thermal stress at outlet. Submerged nozzle depths: 15mm.

**Fig. 9** shows the components of the thermal stress along the transverse direction of the strip at the outlet. Both $\sigma_x$ and $\sigma_y$ keep stable. However, $\sigma_y$ is quite variable, which is in the range of $-2.16 \times 10^5$ to $3.45 \times 10^5$ Pa. It is compressive from 0 - 0.6mm then becomes tensile from 0.6mm to the edge, which means that the defects or cracks would be prone to occur at the strip edge rather than the centre.

![Image](image_url)

**Figure 9.** Thermal stresses along transverse direction at the outlet. Submerged nozzle depths: 15mm. Nozzle spray angle is 10°.

**Fig. 10** shows that two cracks appear at both strip edges in a vertical twin-roll casting strip. This matches the above analysis of thermal stress. This means that the cracks on casting strip in twin-roll casting may be induced by tensile thermal stress along rolling direction due to temperature gradient. So the methods that can reduce temperature gradient then thermal stress at the outlet are beneficial for

![Image](image_url)

**Figure 10.** Cracks on the surface of a casting strip
decreasing the possibility of cracking and improving the quality of casting strip.

**Conclusion**

A numerical simulation based on a 2D finite element model of vertical twin-roll strip casting coupling temperature, flow, and thermal stress has been conducted. The influences of submerged nozzle depth and nozzle spray angles on the temperature-flow-thermal stress fields in the molten pool have been studied.

- The temperature at the outlet increases with an increase of submerged nozzle depth. When the submerged nozzle depth is larger than 20 mm, the temperature at the outlet increases significantly.
- The equivalent thermal stress at the outlet increases with a decrease of nozzle spray angle.
- Tensile thermal stress appears at strip edge and may result in defects and cracks in casting strip.
- Considering the distribution of temperature and thermal stress, the submerged nozzle depth of 20 mm of and nozzle spray angle of 15° may be beneficial for vertical twin-roll casting of magnesium alloy strip.

**References**


