Influence of pouring methods on filling process, microstructure and mechanical properties of AZ91 Mg alloy pipe by horizontal centrifugal casting

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Abstract: Pouring position as the input heat source has great influence on the temperature field evolution. In this study, the Flow3D simulation software was applied to investigate the influence of pouring methods (with fixed or moving pouring channel) on AZ91 Mg alloy horizontal centrifugal casting (HCC) process. The simulation results show that the moving pouring channel method can effectively increase the cooling rate and formability of casting pipe. The casting experiment shows that an AZ91 Mg alloy casting pipe with homogeneous microstructure and clear contour was obtained by the moving pouring channel method, and the grain size of the casting pipe is significantly decreased. Meanwhile, serious macro-segregation appeared in the AZ91 casting pipe by the fixed pouring channel HCC process. Compared with the fixed pouring channel, the moving pouring channel can remarkably improve the ultimate tensile strength and elongation of the AZ91 HCC pipe from 142.2 MPa to 201.5 MPa and 6.2% to 6.7%, respectively.

Key words: horizontal centrifugal casting (HCC); numerical simulation; pouring method; AZ91Mg alloy

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Magnesium is one of the lightest structural metallic materials, which has not only high specific strength and specific stiffness, but also has good thermal conductivity, electromagnetic shielding and mechanical processing properties of shock absorption. Moreover, Mg alloy products can be easily recycled and reused^[1-3]. The advantages of the horizontal centrifugal casting (HCC) process are high efficiency of material utilization and high compact microstructure^[4]. Teng Haitao^[5] observed that compared with the conventional sand casting, the microstructure and mechanical properties of AZ61A magnesium alloy were improved significantly by centrifugal casting.

Numerical simulation attracted more and more interest from researchers and industries due to the advantages of high efficiency and low cost^[4]. Much relevant researching work on the numerical simulation and optimization technology of HCC has been done. For

example, Zeng Xingwang^[6-7], et al. used the centrifugal casting CAE system to obtain an optimal rotation speed, and then predicted the filling sequence, flow pattern, and forecast the time to stop the rotation according to the calculated temperature field during the titanium centrifugal casting filling process.

Pouring position as the input heat source has great influence on the temperature field evolution^[8]. Traditionally, there are two kinds of pouring methods for the HCC process: fixed pouring channel and moving pouring channel. For the fixed pouring channel HCC process, the pouring channel is fixed on one side of the mould during the whole pouring process, while the pouring channel is moving from one side to the other side of the mould for the moving pouring channel HCC process.

The studies on pouring methods of HCC are very limited, and few research studies can be found, especially on the moving pouring channel. In this paper, the HCC flow field and temperature field of AZ91 alloy during the filling process with different pouring methods were investigated systematically by Flow3D simulation software. Besides, the mechanical properties and microstructure of the AZ91 Mg alloy casting pipes made by two kinds of pouring methods were studied.

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1 Simulation modeling

1.1 Boundary and initial condition

The thermal-physical properties of AZ91 Mg alloy used in this study are listed in Table 1 [9].

Table 1: Thermal-physical parameters of AZ91 alloy

Parameter	Value
Density ($\text{g}\cdot\text{cm}^{-3}$)	1.81
Liquidus temperature ($^{\circ}\text{C}$)	595
Solidification latent heat ($\text{kJ}\cdot\text{kg}^{-1}$)	368
Solidus temperature ($^{\circ}\text{C}$)	470
Dynamics viscosity ($\text{Pa}\cdot\text{s}$)	0.00125
Specific heat capacity ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)	1,333
Thermal conductivity ($\text{W}\cdot(\text{m}\cdot\text{K})^{-1}$)	90
Convective heat transfer coefficient between mould and casting ($\text{W}\cdot\text{m}^2\cdot\text{K}^{-1}$)	18,000
Specific heat of mould ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)	590
Convective heat transfer coefficient between mould and air ($\text{W}\cdot\text{m}^2\cdot\text{K}^{-1}$)	400
Convection heat transfer coefficient between casting and air ($\text{W}\cdot\text{m}^2\cdot\text{K}^{-1}$)	200

The length, external diameter, and thickness of the centrifugal casting AZ91 magnesium alloy pipe are 1.2 m, 0.4 m and 0.01 m, respectively. Therefore, the temperature difference of outer and inner layers can be ignored because the thickness is much smaller than other dimensions of the pipe. There are seven monitoring points distributed evenly along the length direction in the middle

pipe wall. According to the Konstantynov formula [4], as shown in Eq. (1), the empirical mould rotation speed is 736 rpm.

$$n = 54570 / \sqrt{\lambda r_0} \quad (1)$$

where n is the rotating speed; λ is unit weight; and r_0 is the inner diameter of cast pipe.

According to studies [10-11], the pouring temperature of the AZ91, the mould temperature, and pouring time are 700 $^{\circ}\text{C}$, 100 $^{\circ}\text{C}$ and 10 s, respectively.

Fig. 1: Schematic diagram of AZ91 pipe

1.2 Meshing

Figure 2 shows the meshed geometry by Cartesian and cylindrical coordinates. The finite volume method was used. The inner face of the mould is rough because the meshes based on rectangular coordinates produce 'stair step' grids [8], as shown in Fig. 2(a), which influence the continuity of flow, for example, at the position of 'stair step', the broken flow stream appeared. In order to make the meshed grids fit the mould surface, meshing based on cylindrical coordinates was adopted, as shown in Fig. 2(b), and the accurate results of flow field during filling process can be achieved.

Fig.2: Comparison of meshing results

1.3 Hydraulics verification

After filling in the rotating mould, the liquid metal flows in two directions: the rotating motion driven by friction force of the inner surface of the mould, and the flow motion along the axial of the mould. Thus, in the centrifugal casting process, the liquid metal should be in the manner of a spiral trajectory. According

to HCC hydraulic experiments carried out by Song Nannan^[12], with the increasing of mould rotating speed, the pitch of the flow stream becomes shorter. The same trend, as shown in Fig. 3, also appears in the simulation results by flow3D software, which means it can achieve good simulation accuracy for the horizontal centrifugal casting process.

Fig. 3: Simulated and hydraulic experimental results of centrifugal casting

2 Simulation results and discussion

2.1 Influences of pouring methods on temperature field

The different temperature fields and filling status of a casting pipe with two kinds of pouring methods are shown in Fig. 4. From Fig. 4(a) with a fixed pouring channel, it can be seen that the outlet of the pouring channel as the input heat source has great influence on the temperature field evolution; the maximum temperature area locates in the position near the outlet of pouring channel. The temperature decreases gradually from the pouring position to the two ends of the mould. At 18 s, the temperature of molten Mg alloy was 412 °C at the 1.0 m point, which means that the liquid metal is solidified and cannot move further to the 1.2 m point. Before 30 s, the 0.12 m monitoring point cannot output the liquid temperature data because the metal liquid does not fill completely. In Fig. 4(b) with a moving pouring channel, the max temperature appears in the range of

0.6–0.8 m after 12 s.

Figure 5 shows the max temperature difference of the casting pipe made by different pouring methods at 6–30 s after pouring. It can be seen that with the fixed pouring method, the value of max temperature difference first increases from 120.3 °C to 181.1 °C, and then decreases to 142.6 °C during 6 s to 30 s. In contrast, the max temperature difference value of the moving channel gradually decreases from 232 °C to 104.5 °C during 6 to 30 s. The relative non-uniform temperature distribution is found along the pipe by fixed pouring channel rather than the moving pouring channel.

Figure 6 shows the evolution of max temperature. When the max temperature of the pipe decreases to 431 °C (eutectic temperature of AZ91), the complete solidification of pipe can be determined. The cooling rate of max temperature by moving pouring channel is higher than by fixed pouring. The solidification time of casting pipe by moving pouring channel was 26.6 s. However, it was beyond 30 s for the pipe by the

Fig. 4: Temperature along pipe's z-axial direction

Fig. 5: Max temperature difference of casting pipe by different pouring methods

Fig. 6: Max temperature of casting pipe

fixed pouring channel process, which means the moving pouring channel improves the solidification velocity of AZ91 alloy.

2.2 Influences of pouring methods on flow field

Figures 7 and 8 show the filling state of pipes with different casting methods at 3 s, 6 s, 9 s, and 12 s, respectively. It can be seen that the filling velocity of the moving pouring channel was faster than that of the fixed pouring channel, because compared with the fixed pouring channel, the moving pouring channel can increase the flow velocity on z-axial direction, which means the movable pouring channel can improve the fluidity of liquid AZ91 alloy.

Figure 9 shows the thickness of the casting pipe (made by two kinds of pouring method) at 30 s. It can be seen from Fig. 9(a) that the thickness of pipe is uneven, which decreases from the pouring position to the other side of the pipe, and the casting pipe contour is incomplete. Because the front of metal stream has been solidified and cannot move further, the metal liquid filling behind stacks on the layer that has already solidified. In Fig. 9(b), the even thickness of casting pipe is obtained.

3 Casting experimental results and discussion

The casting experiment was carried out. Figure 10 shows the appearance of magnesium alloy AZ91 pipe made by fixed pouring channel and moving pouring channel, respectively. Figure 10 (a) shows the uncompleted casting pipe by fixed pouring channel, while in Fig. 10(b), a completed shape and clear contour of pipe was obtained by the moving channel method. The moving pouring channel can effectively improve the filling ability of HCC AZ91 magnesium alloy.

In order to compare the microstructure and mechanical properties between casting pipes by the two different pouring methods, samples for microstructure observation and tensile testing were obtained from the inner layer, middle layer and outer layer of each pipe, as shown in Fig. 11.

3.1 Influences of pouring methods on microstructure

The XRD results of each pipe in different layers are shown in Fig. 12, where it can be seen that the AZ91 mainly composed

Fig. 7: Filling state of pipe with fixed pouring channel

Fig. 8: Filling state of pipe with moving pouring channel

Fig. 9: Wall thickness of casting pipe made by different pouring methods at 30 s: (a) fixed pouring channel, (b) moving pouring channel

of two kinds of phase, i.e., α -Mg and β -Mg₁₇Al₁₂. The wave peak width of Mg₁₇Al₁₂ increases from the inner to outer layer on the fixed pouring channel HCC casting pipe, and the even β -Mg₁₇Al₁₂ peaks at different layers are shown on the moving pouring channel HCC casting pipe. The densities of elements Al ($2.7 \times 10^3 \text{ kg} \cdot \text{m}^{-3}$) and Zn ($7.14 \times 10^3 \text{ kg} \cdot \text{m}^{-3}$) are higher than that of Mg ($1.738 \times 10^3 \text{ kg} \cdot \text{m}^{-3}$), and the Al and Zn would move toward the outer layer of the casting pipe under centrifugal force. Thus, the content of β -Mg₁₇Al₁₂ increases from inner to outer layers. According to the simulation result mentioned above, the solidifying time of the casting pipe made by fixed pouring channel is longer than that of moving pouring channel, which means under centrifugal force, the Al element has enough time to move from inner layer to outer layer, which caused the different content of β -Mg₁₇Al₁₂ phase in different layers of the pipe formed by fixed pouring channel.

Figure 13 shows the microstructures of HCC AZ91 casting pipe made by fixed pouring channel and moving pouring channel. It can be seen that the inhomogeneous phase distribution and the difference of grain size is obvious for the fixed pouring channel casting pipe, i.e., the size of β -Mg₁₇Al₁₂

(a) Fixed pouring channel

(b) Moving pouring channel

Fig. 10: Appearance of casting pipes made by different pouring methods

Fig. 11: Position of samples for microstructure observation and tensile test

Fig. 12: XRD results of AZ91 alloy

Fig. 13: Microstructure of AZ91 casting pipe on different layers: (a to c) fixed pouring channel; (d to f) moving pouring channel; (a and d) inner layer; (b and e) middle layer; (c and f) outer layer

increases from inner to outer layer. In Fig.13(c), the networked shape of $\beta\text{-Mg}_{17}\text{Al}_{12}$ appears between grains. However, it is hard to find $\beta\text{-Mg}_{17}\text{Al}_{12}$ in Fig. 13(a). It can be seen from Fig. 13(d) to (f) that the grain size of the moving pouring channel HCC casting pipe is decreased significantly, and the average grain size decreases to $13.5\text{ }\mu\text{m}$ with a reduction of approximately 60% compared with that of $24.1\text{ }\mu\text{m}$ by fixed pouring channel. The refinement mechanism can be described as: according to the metal solidification theory, the material nucleation rate in per unit time was proportional to the solidifying velocity. According to the simulation result, the moving pouring channel would improve the cooling rate of liquid metal. Consequently, the grains of HCC casting pipe would be refined significantly by the moving pouring channel pouring method. At the same time, the longer solidification time of the casting pipe by fixed pouring channel leads to the coarser grain size and the macro-segregation.

3.2 Influences of pouring methods on mechanical properties

Figure 14 shows the tensile strength of two pipes in different layers. It can be seen that from inner to outer layer, the tensile strengths of the casting pipe made by fixed pouring channel are 134.6 MPa, 142.2 MPa and 106.5 MPa, respectively. While for the pipe formed by the moving pouring channel, they are 198.1 MPa, 201.5 MPa, 195.8 MPa, respectively. Compared with that by fixed pouring channel process, the average value of AZ91 tensile strength increased about 55% by using the moving pouring method. Figure 15 shows the elongation of two pipes in different layers. It can be seen that by using the moving pouring channel, the AZ91 elongation is almost at the same level of about 6.4%. However, from inner to outer layer, the elongation decreases from 6.2% to 3.3% by using the fixed pouring channel. According to the Hall-Petch relationship, the tensile strength of material is inversely proportional to grain

Fig. 14: Tensile strength of AZ91 on different layers of casting pipe

Fig. 15: Elongation of AZ91 on different layers of casting pipe

size, which means the refined grain size obtained by using the moving pouring channel can improve the tensile strength of AZ91. Besides, the brittle fracture of $\beta\text{-Mg}_{17}\text{Al}_{12}$ was harmful for the tensile strength and elongation of AZ91^[13]. Thus, the segregation of $\beta\text{-Mg}_{17}\text{Al}_{12}$ in the outer layer of the casting pipe would significantly reduce the mechanical properties.

4 Conclusions

Through numerical simulation and experimental research, the following conclusions can be obtained:

(1) The moving pouring channel is a more suitable pouring method for HCC AZ91 casting pipe than the fixed pouring

channel, and it can obtain a uniform temperature field and higher solidifying velocity.

(2) The experimental results show that the macro-segregation appeared in the casting pipe made by the fixed pouring channel HCC process. The microstructure of AZ91 casting pipe is homogeneous by the moving pouring channel, but not by the fixed pouring channel. The grains of the casting pipe made by the moving pouring channel HCC is refined significantly. Compared with the fixed pouring channel, the moving pouring channel can remarkably improve the ultimate tensile strength and elongation of the AZ91 HCC pipe, which increase from 142.2 MPa to 201.5 MPa and 6.2% to 6.7%, respectively.

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