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The Effect of Casting Speed on Physical Fields of AZ80 Magnesium Alloy during DC Casting

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Abstract. A comprehensive two-dimensional (2D) mathematical model based on a combination of the commercial finite element package ANSYS and the commercial finite volume package FLUENT was developed to describe the interaction of the multiple physics fields during DC casting process. ANSYS was for calculation of the stress field and FLUENT was for calculation of the fluid flow, heat transfer of the solidification. The results show that: the model is reliable and accurate to simulate the multiple physics of DC casting. Consequently, the position, which was prone to hot tearing, was confirmed and the max velocity, at which the hot cracking might not occur, was determined. The numerical simulations will be very useful for preventing crack, optimizing casting parameters and obtaining high-quality ingots.

Introduction

With the increasing concern of government and the public concern on energy-saving and environmental protection, the demand for lightweight in the automobile industry is becoming even more urgent. Magnesium alloy has many potential applications in various fields, such as automobile industry, 3C products and rail transport industry etc.[1-5] Currently, it is well known that direct-chill (DC) casting is the most important process to obtain cast magnesium alloys. Hot cracks appear due to the asynchronous of constriction caused by the different cooling rate of the different parts of billets during the solidification of the alloy, the most important casting parameter that affects hot tearing is the casting speed. Therefore, it is important to eliminate and inhibit the generation and expansion of cracks in order to improve the quality of ingot.

Over the last decade, investigation on the casting cracks of magnesium alloys have been reported in many previous studies. M.G. Pokorny et al [6]investigated the simulation of stress during casting of binary magnesium-aluminum alloys. In this investigation an analytical model was proposed to predict hot tears for Mg-1 and 9 wt. % Al alloys. Ishikawa et al[7]studied the high strain rate deformation behavior of an AZ91 magnesium at elevated temperature. They showed that the operating deformation mechanisms at high strain rated were suggested to be dislocation glide and twinning even at elevated temperatures. Helis [8] presented the microstructure evolution and texture development during high-temperature uniaxial compression of magnesium alloy AZ31. Hao, H et al[9] built a modeling assessing the impact of casting speed on the hot tendency in AZ31 billets. It is costly and time consuming and may be impossible in some cases for experiment. Therefore, it is necessary to develop computer simulation to study the effect of temperature field and stress field on hot tears.

The aim of this article is to analyze the effects of casting speed on temperature field and stress field of AZ80 alloy during DC casting. The analysis is based on the systematic numerical simulation of billets of AZ80 alloys cast at different casting speeds. Thermomechanical behavior of a solidifying billet is combined with available hot-tearing criteria, and the regularities of stress field are found out at different casting speed, which provided reference for avoiding the crack.

Numerical Simulation

A constitutive model to represent the viscoplastic behavior on account of incremental theory was described by the following equation:

$$\{d\sigma\} = [\mathrm{D}]_e \{\mathrm{d}\,\varepsilon_e\} \tag{1}$$

where $\{d\sigma\}$ is the stress increment, $[\mathrm{D}]_e$ is the matrix of elastic modulus, $\{\mathrm{d}\,\varepsilon_e\}$ is the elastic strain increment.

The total strain increment including the sum of the thermal, elastic and viscoplastic strain increment, can be expressed as:

$$\{\varepsilon\} = \{\mathrm{d}\,\varepsilon_e\} + \{\mathrm{d}\,\varepsilon_p\} + \{\mathrm{d}\,\varepsilon_{th}\} \tag{2}$$

The thermal strain increment is calculated using the volume change caused by change in temperature, as a function of temperature:

$$\{\mathrm{d}\,\varepsilon_{th}\} = \{\alpha(\mathrm{T})\Delta\,\mathrm{T}\} \tag{3}$$

where $\alpha(\mathrm{T})$ is the temperature dependences of thermal expansion.

The strain increment in plastic zone is given by equation (4):

$$\{\mathrm{d}\,\varepsilon_p\} = \lambda\{\frac{\partial Q}{\partial\sigma}\} \tag{4}$$

where λ is the plasticity multiplier, Q is the plastic power.

Hence, the stress increment $\{d\sigma\}$ is decided by equation (5):

$$\{\mathrm{d}\,\sigma\} = [\mathrm{D}]_e(\{\mathrm{d}\,\varepsilon\} - \{\mathrm{d}\,\varepsilon_p\} - \{\mathrm{d}\,\varepsilon_t\}) \tag{5}$$

Initial conditions:

The casting temperature is initialized by the pouring temperature. The initial temperature of mold, water and dummy bar head are the same. In this paper, the value is 293K.

Boundary conditions:

The heat transfer is divided into two zones during the DC casting, that is, mold zone and secondary cooling zone. In every zone, the boundary condition is complex and different. The thermal boundary condition is formulated according to Eq. (6)

$$k_{thermal}\frac{\partial T}{\partial n} = [h_{contact}(1-f_s) + h_{air} * f_s](T - T_{en}) \tag{6}$$

where T_{en} is environment temperature and its value is 323K; $h_{contact}$ the thermal contact between the mold and the melt and its value is 3000Wm^{-2}K^{-1}, h_{air} is 100 Wm^{-2}K^{-1} . But in the secondary cooling zone, the heat transfer coefficient is the function depending on temperature.

Materials Data

The material used in this study was an as-cast AZ80 magnesium alloy with a main composition of Al 7.9–9.2, Zn 0.7–0.8, Mn 0.12–0.15, Y 1 and Mg balance. Thermophysical properties of AZ80 magnesium alloy, such as specific heat, thermal conductivity, Young's modulus and thermal expansion coefficient, were taken from the software JMatPro as temperature-dependent characteristics. These parameters are shown in Fig.1 and Fig.2. The other properties are as follow: Poisson's Ratio is 0.35; Density is 1806kg/m. The liquidus and solidus temperature predicted by

JMatPro are 880K and 670K for AZ80 alloy, respectively. The crystallizer is made in aluminum. Moreover, duo to the lack of the data, except for the initial yield stress at temperatures below 573K, the mechanical properties needed in the stress model were estimated from data available in the literature[10-14].

A DC cast billet 160 mm in diameter and 1780 mm in length was simulated. A quarter of the billet is analyzed in consideration of symmetrical shape and reducing the quantity of calculation in this work. The computation of finite-element model (FEM) of billet is based on above thermal and mechanical properties. Interpolation method is used in this work. Firstly, the transient temperature field and flow field are calculated by Fluent software; then, the calculated temperature is imputed into Ansys software to calculated the stress field which is carried out by Ansys software.

In order to investigate the effects of speed on the hot cracks, all casting process parameters except speed are fixed and the casting speed is 0.0014m/s, 0.0019m/s, 0.0024m/s and 0.0029m/s, respectively.

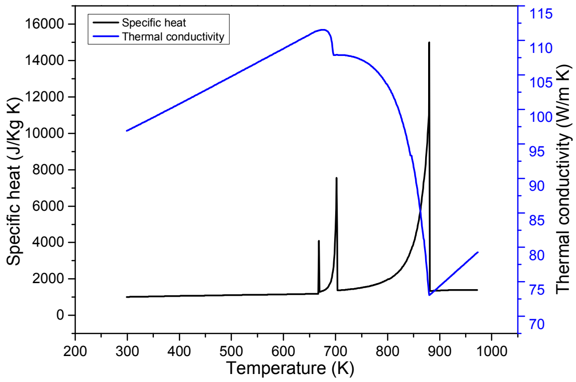

Fig.1. The values of specific heat and thermal conductivity

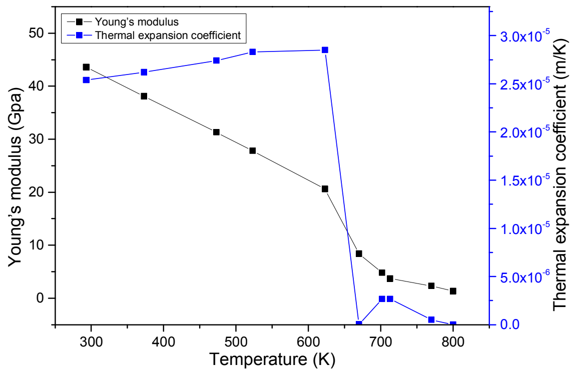

Fig.2. The values of Young's modulus and thermal expansion coefficient

Results and Discussion

Effect of casting speed on temperature fields. Fig. 3 shows different speed of the temperature profiles. It is found that the casting speed has great influence on the temperature field. The liquidus of alloy moves downwards with the increase of casting speed. The sump shape and sump depth under different velocities are shown in Fig. 4(a and b), respectively. It is observed that the velocity has no impact on sump shape and has great impact on sump depth. As seen from Fig. 4, an increase in the sump depth and the mushy zone thickness, and an overall acceleration of solidification when the casting speed increases. All these correspond to the conclusion from Livanov, VA [15]. There exists a good linear correlation between the casting speed and sump depth. It will help to increase the tendency of crack usually. The liquidus locates under the mould when the casting speed is 0.0024m/s and 0.0029m/s, and it is very dangerous for DC casting. Hence, reducing casting speed, the difference of cooling velocity between inside and outside of billets will decrease, which will result in letting up the appearance of crack.

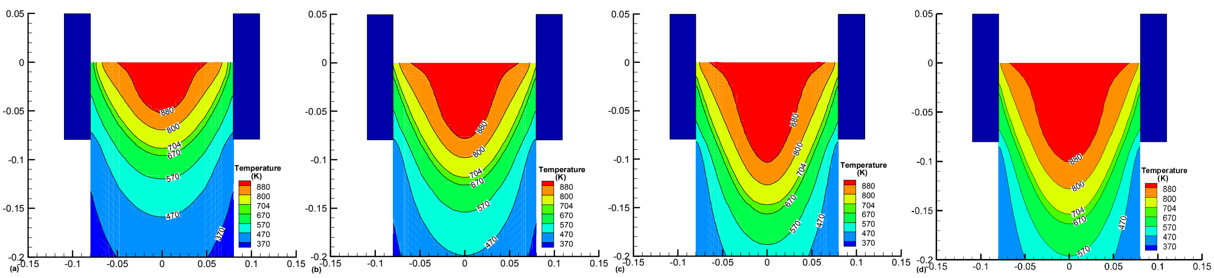

Fig. 3 Temperature field of different casting speed: (a) 0.0014m/s (b) 0.0019m/s (c) 0.0024m/s (d) 0.0029m/s

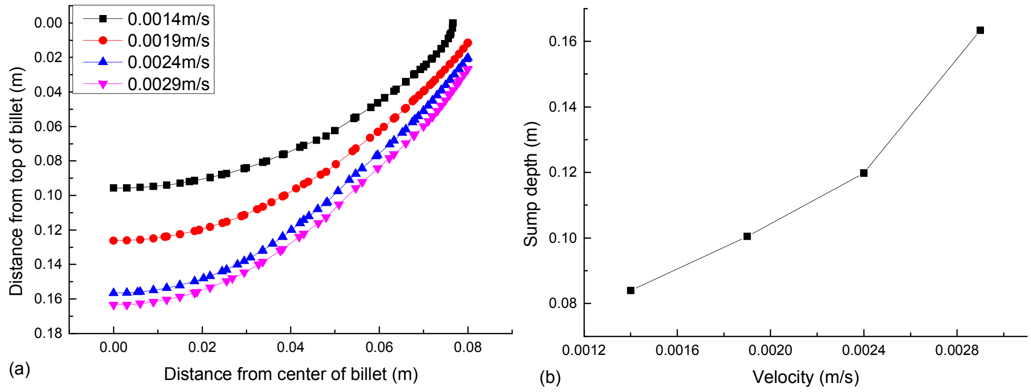

Fig. 4 Effects of casting speed on (a) sump shape and (b) sump depth

Effect of casting speed on flow fields. Fig. 5 shows the velocity vectors with temperature contours of melt under the different casting speed. It is found that the velocity vectors of melt increases with increasing of casting speed, and the penetrability of melt increases obviously, when the melt is poured from inlet to the mold. There is a re-circulation zone in the whole flow field. The area of re-circulation zone increases with downwards of liquidus due to the increase of casting speed. As the existence of re-circulation, the velocity of the given path decreases firstly, then increases to a certain limit and finally reduces to zero.

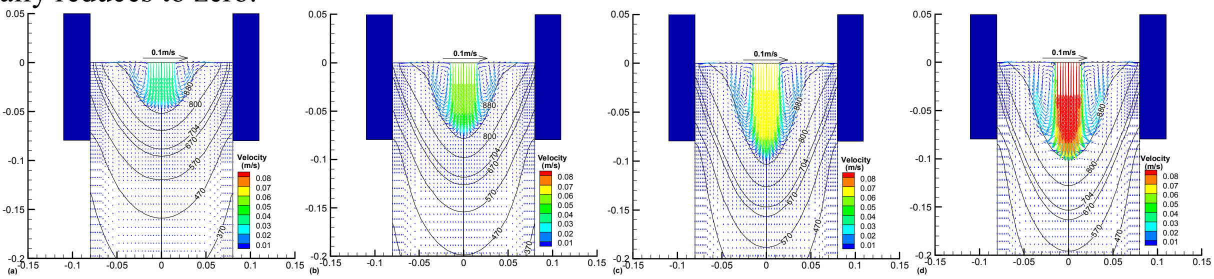

Fig. 5 Velocity vectors with temperature profiles under different casting speed: (a) 0.0014m/s (b) 0.0019m/s(c) 0.0024m/s (d) 0.0029m/s

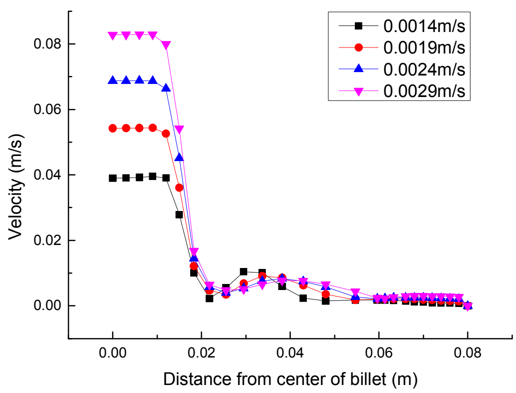

Fig. 6. Velocity of melt on the given path(y=0.01 in Fig. 3) under different casting speed

Effect of casting speed on stress fields. The equivalent plastic stress profiles in the billets in DC casting when velocity is in the range of 0.0014-0.0029m/s are shown in Fig. 7. It is found that the stress generated in the DC casting process increases with the increasing of velocity, which results from the temperature field modified by the variations in temperature. Further, all the occurrence of the stress concentration is in the center of billets. Therefore the position the easiest to crack is the center of billets, and the conclusion agrees the fact. When the melt is poured into liquid pool from the inlet and flows downwards along the symmetry axis to reach the solidification front, forming a certain thickness solid shell. The inside of solid shell is liquid, and outside is solid. So the cooling rate of inside is slow and outside is quick. The synchronous of solidification between inside and outside of billets causes' the center of billet is tensile stress and surface of billet is compression stress. So there may be center crack on the effect of tensile stress. In order to reduce the propagation of crack, the casting speed should be decreased to reduce the difference of cooling rate between inside and outside of billets. Fig.8 shows the maximum of equivalent plastic stress of billet under different casting speed. The tensile strength of AZ80 magnesium alloy is 170MPa. It is observed that the maximum of equivalent plastic stress exceeds the tensile strength when the casting speed is 0.0029m/s. Hence, the casting speed of AZ80 magnesium alloy is less than 0.0029m/s.

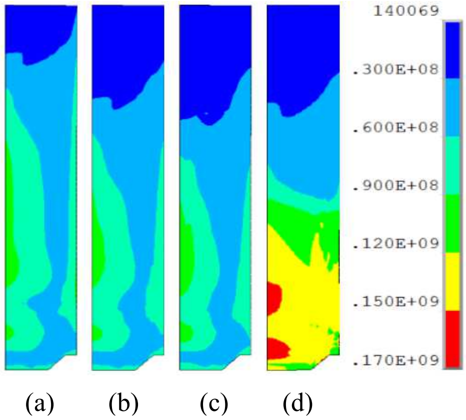

Fig. 7 Equivalent plastic stress under different casting speed: (a) 0.0014m/s (b) 0.0019m/s (c) 0.0024m/s (d) 0.0029m/s

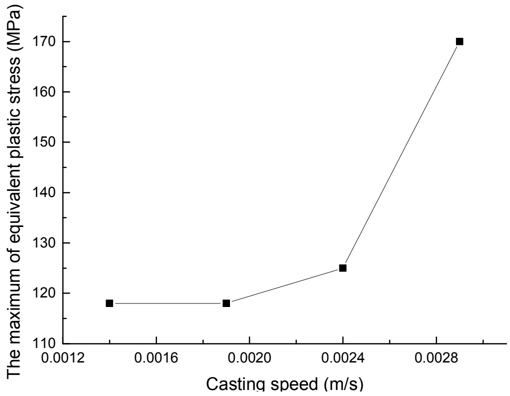

Fig.8. The maximum of equivalent plastic stress under different casting speed

Conclusion

According to the above simulations, we can draw the following conclusions:

(1) A comprehensive mathematical model has been developed to describe the temperature field, flow field and stress field during DC casting process.

(2) The sump depth, velocity of melt and the equivalent plastic stress increase with the increase of casting speed.

(3) The center of billet is the easiest position to crack. The decrease of casting speed can inhibit the cracking initiation. And the casting speed is less than 0.0029m/s.

Acknowledgments

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