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Numerical simulation and experimental research on the cooling-controlled technology for high strength aluminums alloy ingots

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The temperature field and stress state of 7050 high-strength alloy ingot were simulated with the help of commercial package FLUENT and ANSYS. In order to verify the mathematic model and the boundary conditions applied in the simulation, the temperature field of 7050 ingot was calculated and compared with the experimental results during the conventional casting and cooling-controlled casting, respectively. The simulated results were in good agreement with the experimental measurements. The simulation for residual stress inside the ingot shows that the skin of the ingot appears to be in a compressive stress state and the core is in a triaxial tensile stress state in the steady-state casting. After applying the panels, the thermally induced stresses inside the ingot are decreased.

Key words：*DC casting; water-restricted panels; numerical simulation；temperature field; stress state.*

1. Introduction

The industry produces extrusion billets and rolling-sheet ingots mainly by the direct-chill (DC) casting process. Direct chill casting is a semi-continuous process in which molten aluminum enters the top of a water cooled mold, while a solid ingot is drawn from below. The molten aluminum begins to solidify as it comes into contract with the mold wall, forming a thin solid layer around a liquid melt, commonly refereed to as the sump. As soon as the solidified shell is strong enough to embay the molten metal inside, the ingot is withdrawn from the bottom of the mold and water jets impinge on the surface, directly cooling and completely solidifying the ingot.

At the early stage of the research, trial-and-error method was applied to investigate the DC casting process and the attention was focused mainly on the industry experiments. With the development of powerful numerical method and computers, simulations are used increasingly in order to understand the semi-continuous casting process, which significantly reduces the developing cost and shortens the research period.

2××× and 7××× aluminum alloys exhibit a wide solidification range and the ingots are hard to produce because cracks usually occur during the casting [1, 2]. Some techniques were being further developed to suppress the cracking. P.P. Zeigler invented the cooling-controlled technology for continuously cast ingots, which applied water-restricted panels during the casting and removed the coolant from the ingot surface [3].

In this paper, computer simulation with the help of commercial software FLUENT and ANSYS was carried out to the DC casting process of 7050 high-strength alloy. Base on the reported results [4~6], a comprehensive mathematic model was developed and the boundary conditions of the mathematic model was optimized to calculate the temperature fields by using FLUENT. A linear interpolation method was used to calculate the stress state by using ANSYS [7]. The changes of temperature field and stress state of the ingot cast by the conventional process and the cooling-controlled technology were simulated, respectively.

2. Simulation procedure

DC casting process for an 180×360mm^2 rolling ingot of 7050 alloy is simulated with a total length of 1200mm. One quarter of the ingot was modeled for symmetry reasons and the computation domain is shown in Fig.2. According to the hydrodynamic law, the following conservation equations must be obeyed, which can be written as:

Conservation equation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{1}$$

Conservation equation of momentum:

$$\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U U) = \nabla \cdot (\mu_{eff} \nabla U) - \nabla P + S_m \tag{2}$$

Conservation equation of energy:

$$\frac{\partial (\rho T)}{\partial t} + \nabla \cdot (\rho U T) = \nabla \cdot (\frac{k}{c_p} \nabla T) + S_{th} \tag{3}$$

where μ_{eff} and S_m are effective viscosity coefficient and momentum source in the equation (2), respectively. The μ_{eff} is given by $\mu_{\mathrm{eff}} = \mu_1 + \mu_{\mathrm{t}}$, where μ_1 is laminar viscosity in the liquid and μ_{t} is turbulent viscosity. The S_m includes thermal buoyancy and Darcy source term. The S_{th} in the equation (3) is thermal source and includes latent heat of solidification. The method of the equivalent heat is used to treat the latent heat of 7050 for modeling the energy transport. The equivalent specific heat C^* is written as:

$$C^*(T) = C_S(T) \times f_S + C_1(T) \times f_1 - \nabla H_f \times \frac{\partial f_S}{\partial T} \tag{4}$$

Where C_S is the specific heat of the solid, C_1 is the specific heat of the liquid and ∇H_f is the latent heat of fusion; f_S and f_l are the solid and liquid volume fraction, respectively.

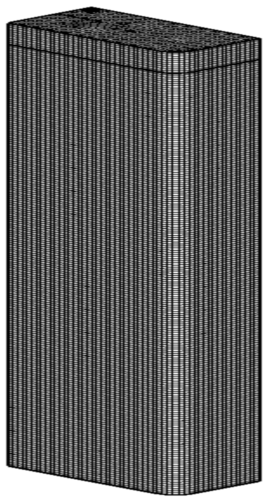


Figure 2 Computation domain of the ingot

The 7050 alloy is used for the casting investigation and its physical properties are listed in table 1. The density and viscosity of the alloy were treated as constant value in the calculation. The mechanical properties of 7050 alloy are from the reported results [8].

Table 1 Material parameters of 7050 alloy

Density(Kg/m^3)	Viscosity coefficient(Pa•s)	Solidus temperature (K)	Liquidus temperature (K)
2830	0.001	737	907

In order to validate the model and the simulation results, the casting experiments of 7050 ingots were carried out in our laboratory. The ingots were cast under the following conditions: casting speed, 75mm/min; melt temperature at the launder, 710°C; and water flow rate, 74L/min. The ingot cross section was 180×360mm^2 and the ingot length was 1200mm. Both conventional DC casting and cooling controlled casting were experimentally investigated. In the cooling controlled casting, the water-restricted panels were applied below the mold with the distance of 130mm.
Fig.5 shows the schematic diagram of temperature measurement. Four K-type thermocouples were fixed on the four steel rods, which welded to the starter block before casting. During the casting, these thermocouples moved with the starter block and were frozen into the solid metal. In this way, the cooling histories at the locations of ingot center, ingot corner, rolling face centerline and narrow face centerline, respectively, were obtained and compared to the calculated results.

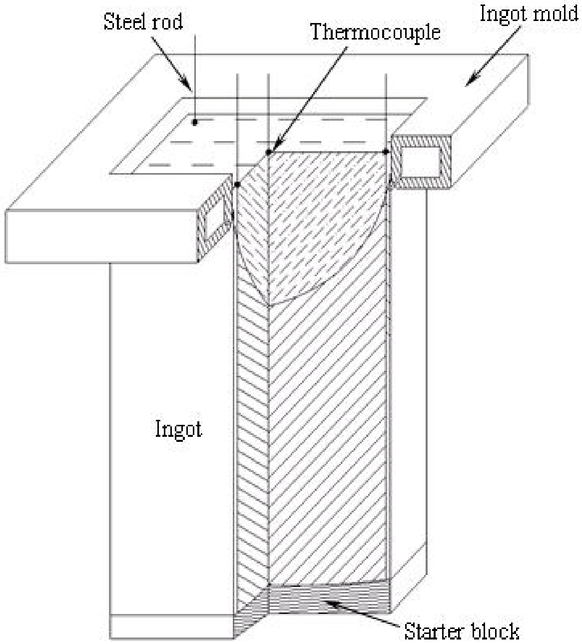


Fig.5 Schematic diagram of the temperature measurement

3. Results and discussion

Fig.6 shows the measured cooling histories of 7050 ingots cast with and without the water-restricted panels. Fig.6(a-d) represents the positions of ingot center, ingot corner, rolling face centerline and narrow face centerline, respectively. The temperature inside the ingot decreases with the increase of the distance to the liquid surface. The temperature at the ingot surface decreases much faster than that at the ingot center due to the chilling effects by the cooling water. After applying the water-restricted panels, the change of temperature curves at the ingot center more slowly than that cast during the conventional casting process. Below the panels, an increase in temperature was obtained at the regions close to the ingot surface. The cooling rate throughout the ingot, especially close to the surface, was reduced by applying the panels, which removes the cooling water from the ingot surface.

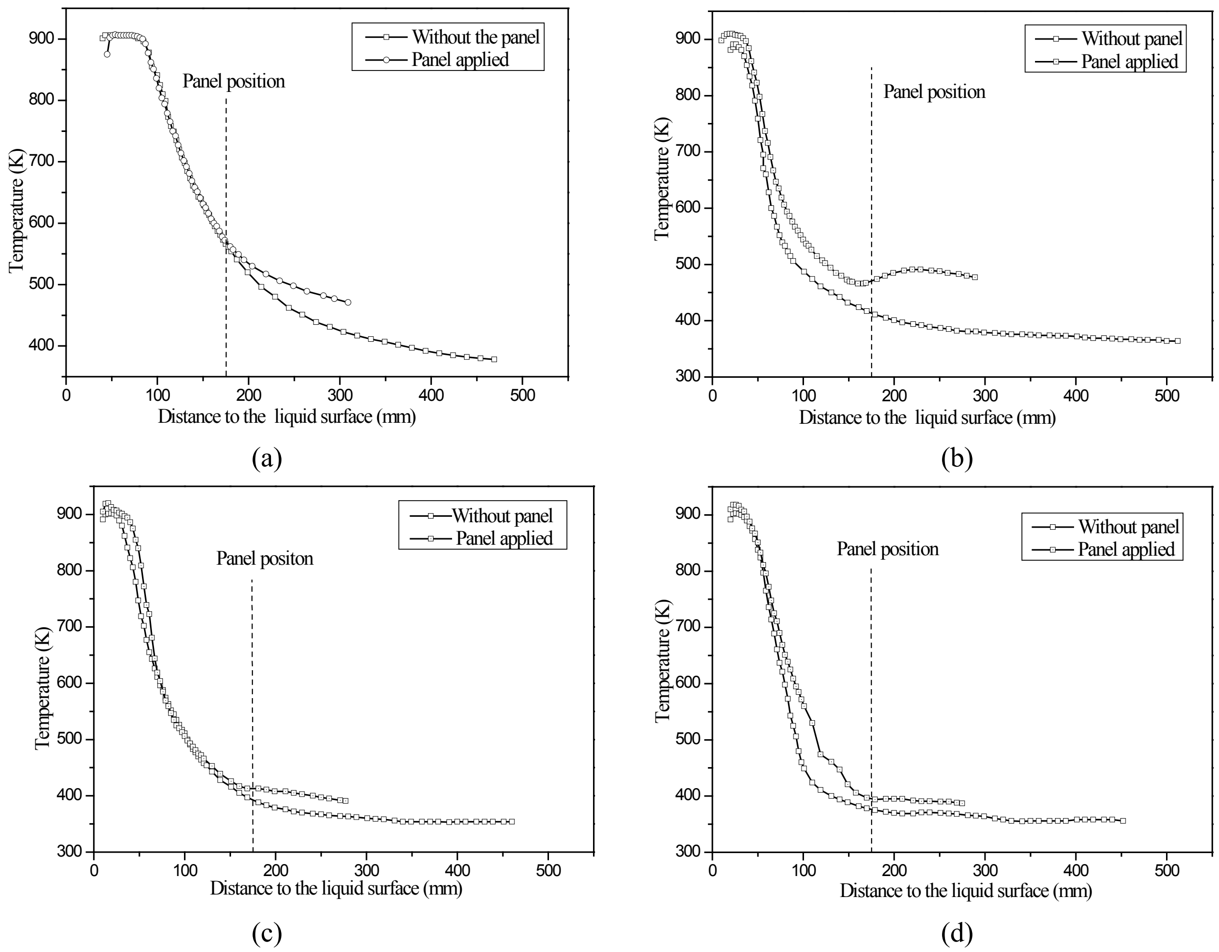
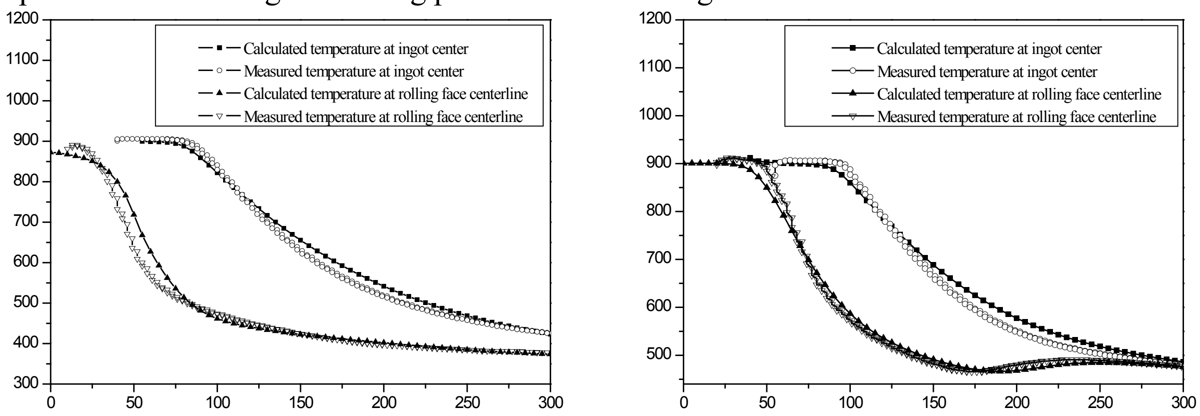


Fig.6 The measured cooling history of 7050 ingot cast with and without the water-restricted panels:
(a) ingot center; (b) rolling face centerline; (c) narrow face centerline; (d) ingot corner

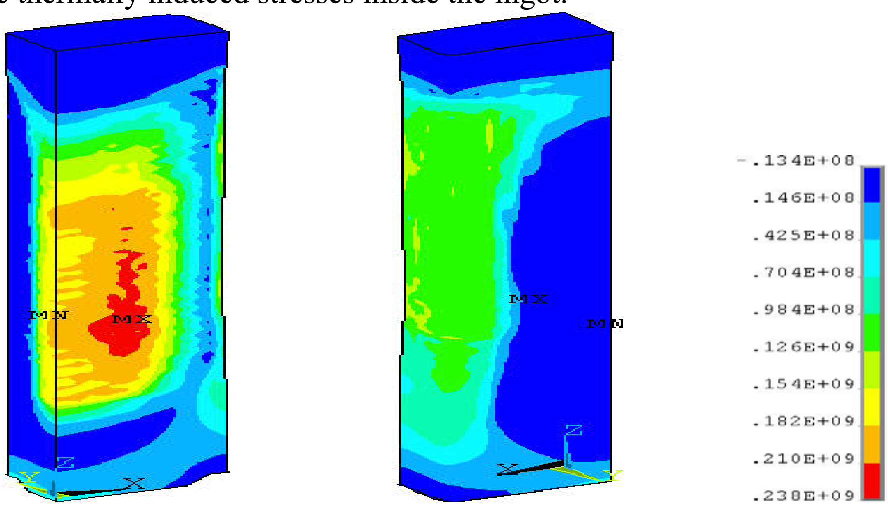
Fig.7 shows the temperature comparison between the calculated and measured results for the ingot cast by the two processes. Temperature curves at the ingot center and rolling face centerline were selected. There is a good agreement between the calculation and measurement regardless of the conventional DC casting, Fig.7(a), and the application of the water-restricted panels, Fig.7(b). These agreements indicated that the applied model and boundary conditions in the calculation are appropriate for simulating the casting processes of 7050 ingots.



(a) (b)

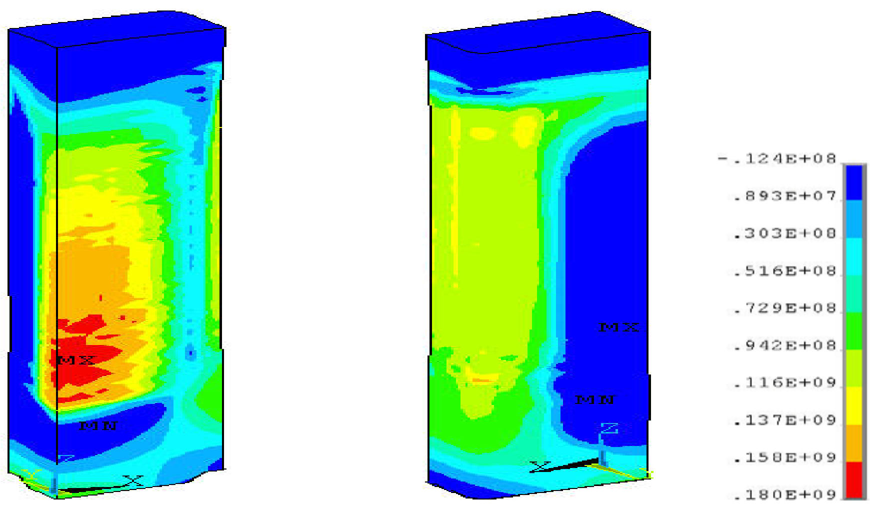
Fig.7 Comparison between the calculated and measured temperature curves:
（a）conventional DC casting, （b）the water-restricted panels applied.

Fig.8 shows the simulated major principle stresses remaining in the ingots during the steady-state conditions. During the steady state of DC casting, the skin of the solidified ingot appears to be in a compressive stress state, whereas the core is in a triaxial tensile stress state. This is caused by the fact that the cooling water impinges on the ingot surface and generates a large difference in temperature between the skin and the core of the ingot. During the casting, the solidification contraction at the ingot core is prevented by the surface layer as solidification proceeds, which causes the formation of tensile stress in the ingot center [8]. The stress state in the solidified ingot results from a balance between tensile stresses in the ingot core and compressive stresses in the skin. It is also obvious from Fig.8 that the tensile stress reaches its maximum in the ingot core and the part of the zone with high tensile stress is very wide. After applying the panels, the simulated major principle stress in the ingot is shown in Fig.9. The stress states in the skin and the core of the solidified ingot are not changed. However, the magnitude of stress in the solidified ingot is decreased and the part of the zone with high tensile stress is narrower. The authors believe that the modified stress of the ingot is due to the changed temperature field by the applied panels. From measured and calculated results in Fig.6 and Fig.7, temperature increases were observed in the ingot below the applied panels, which deceases the temperature difference between the ingot core and skin. During the following casting, the ingot core and skin may solidify and contract simultaneously, which reduces the thermally induced stresses inside the ingot.



(a) (b)

Fig.8 Principle stresses in the ingot cast in the conventional conditions, (a) ingot core (b) ingot skin



(a) (b)

Fig.9 Principle stresses in the ingot with the application of panels, (a) ingot core (b) ingot skin

4. Conclusions

In this study, the temperature field and the stress state of 7050 high-strength alloy ingot were simulated with the help of commercial package FLUENT and ANSYS. 7050 ingots were cast in the conventional DC casting and in the cooling-controlled process, in which the water-restricted panels was applied. Temperature changes inside the ingots were measured and compared to the simulated results. There is a good agreement between the measurement and the calculation. The simulation for residual stress inside the ingot shows that the skin of the ingot appears to be in a compressive stress state and the core is in a triaxial tensile stress state in the steady-state casting. After applying the panels, the thermally induced stresses inside the ingot are decreased.

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