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Numerical simulation of temperature and strength distributions of mold(core) on heating ①

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[Abstract] By using Visual C++, a model with post-processing was carried out to simulate the temperature and strength distributions of the mold(core). The results are shown in 256-color graphic mode. With this model, the temperature and strength distributions of the mold(core) both in case of heating process for core in the furnace and solidification process for a thin-wall aluminum alloy casting in the mold(core) are numerically simulated. The results show that the temperature and strength distributions of the mold(core) were uneven because the thermal conductivity of the resin sand was much small. This study laid a basis for the optimum design of the mold(core) properties.

[Key words] mold(core); numerical simulation; temperature distribution; strength distribution

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1 INTRODUCTION

It is an important developing direction to produce thin-wall aluminum alloy casting by using resin sand mold(core), which demands that the resin sand has appropriate high-temperature strength and lower high-temperature retained compression strength. In recent years, a number of researches on resin sand have been done and many useful experimental results have also been achieved by scholars[1]. Richard et al[2] treated the surface of silicon sand with acid, which apparently enhanced the strength of furan resin sand. MENG et al[3] greatly improved the decomposing degree of resin sand used in producing thin-wall aluminum alloy castings by mixing 304 resin with urea resin. Ashland Co. developed polyurethane resin sand with high room temperature strength and good decomposing degree. However, the requirements for the properties of the mold(core) are different due to the complicated producing conditions.

The molten metal filling process and the casting solidification process can be quantitatively studied by using numerical simulation technique. The simulated results, such as the flowing field and temperature distributions can be displayed visually, so it has a unique advantage[4, 5]. In Refs.[6, 7] and Ref.[8], the filling process of the molten metal in traditional casting and the solidification process of casting were numerically simulated, respectively. The flowing and heat transfer in lost form process were simulated in Ref.[9]. Brown et al[10] carried out the computer simulation of grain growth and microstructure development during solidification. Up to now, numerical simulation techniques are applied widely in researching the flowing of molten metal, the solidification of casting, the microstructure of casting and the prediction of defects, and so on. Furthermore, many commercial softwares were developed[11]. However, the numerical simulation study on temperature and strength distributions of mold(core) on heating was seldom, which is not of benefit to the optimum design of the mold(core) properties.

In this paper, the temperature and strength distributions of mold(core) on heating are numerically simulated. This study can supply a basis for the optimum design of the mold(core) properties.

2 NUMERICAL SIMULATION MODEL

2.1 Heat transfer governing equation and discretization

The heat transfer governing equation of the mold (core) on heating was Fourier partial differential equation. Thinking that the molten metal will release its latent heat during solidification, a continuity equation is used to describe the heat transfer in the casting and the mold(core). The expression of the heat transfer equation is as follows:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + \theta \rho L \frac{\partial f_s}{\partial t} \tag{1}$$

where θ—the characteristic parameter, $\theta = 1$ for the casting and $\theta = 0$ for the mold(core); λ—thermal conductivity; c_p—constant-pressure specific heat; L—latent heat of solidification of casting; $\frac{\partial f_s}{\partial t}$—rate of change of solid fraction.

The casting and the mold(core) were divided by

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using the right-angle hexahedron grid in this study, and the finite difference form was used to establish the discretization equation of equation (1), its expression is

$$\rho_i C_i(\Delta x\,\Delta y\,\Delta z)\,\frac{T_i^{t+\Delta t}T_i^t}{\Delta t} =$$

$$\sum_{j=1}^{6}\frac{S_{i,j}}{\frac{1}{h_{i,j}}+\frac{d_{i,j}}{\lambda_i}+\frac{d_{i,j}}{\lambda_j}}(T_j^t - T_i^t) \qquad (2)$$

where Δx, Δy, Δz —space step in x, y and z directions, respectively; Δt —time step; $S_{i,j}$ —area between element i and j; d_i —distance from the nodal point of element i to the interface between element i and j; $d_{i,j}$ —distance from the nodal point of element j to the interface between element i and j; $h_{i,j}$ —heat transfer coefficient between i and j; λ_i, λ_j —thermal conductivity of element i and j, respectively.

2.2 Calculation equation of strength

In the earlier study, the resin sand was fabricated into d30mm × 30mm samples and the compression strength of the samples heated at 300 ℃, 400 ℃, 500 ℃ and 600 ℃ respectively was measured. For each heating temperature, there are five heat treatment times, i. e. 1 min, 3 min, 5 min, 7 min and 9 min. The results are shown in Table 1.

Table 1 High temperature strength of resin sand (MPa)

Time / min	Temperature/ ℃			
	300	400	500	600
1	3.18	2.94	2.55	2.02
3	2.76	2.49	2.09	1.54
5	2.45	2.05	1.63	1.07
7	1.89	1.60	1.16	0.59
9	1.46	1.15	0.78	0.11

An empirical equation was established by regression analysis of the data, which revealed the change of strength of mold(core) with the heating temperature and time. The equation is as follows:

$$\sigma = 3.277 - 0.19t + 0.0025T - 0.0002t^2 - 0.000007T^2 - 0.000078Tt \qquad (3)$$

where σ is the high-temperature compression strength, T is the heating temperature and t is the heating time.

2.3 Treatment of boundary conditions

It is difficult to describe the heat transfer between the casting and mold(core) accurately during the solidification of casting. In this study, an empirical equation offered in Ref. [12] was used to calculate the heat transfer coefficient between the casting and mold(core). The convective and radiative heat transfer between mold and air or between core and high temperature gas should be considered. The effective heat transfer coefficient was calculated in light of an empirical equation offered in Ref. [12].

2.4 Treatment of latent heat

Eutectic aluminum silicon alloy was used in this study, and latent heat was treated by using temperature rise again method, in which the increment of the solid fraction Δf_s was used to replace the release of the latent heat. The expression is

$$\Delta f_s = c_p\,\Delta T/L \qquad (4)$$

where ΔT is the temperature drop of all element in a time step. When $\sum \Delta f_s = 1$, it means that all latent heat had been released.

2.5 Post-procession of simulated results

Using Visual C++ language and OOP technique, a post-processing software of numerical simulation was developed. The numerical simulation results were displayed with 256-color graphic mode. The results showed that the temperature and strength distribution displayed by using the developed post-processing software were visualized and the post-processing graph color transition was smooth and accurate.

3 NUMERICAL SIMULATION RESULTS

By Eqn. (2), the temperature distribution of the mold(core) on heating can be obtained. To simulate the strength distribution of the mold(core), first, the simulated temperature of each mesh cell is interpolated, then the treated temperature and heating time are introduced into Eqn. (3) to calculate the strength distribution of the mold(core).

Fig. 1 displays the simulated temperature distribution when the core is heated in a furnace. The size of the core is d30mm × 30mm, and the core-making material is furan resin sand. The temperature in the furnace is 600 ℃. Both the top and the bottom surfaces of the core are assumed to touch with the room temperature mold tightly, and only the lateral surface of the core is heated by high temperature gas in the furnace.

It is seen from Fig. 1, the temperature distribution of the core is much uneven since the thermal conductivity of the resin sand core is lower. The temperature of the core surface is about 200~ 300 ℃ higher than that of the core center.

Fig. 2 shows the numerical simulated results of the strength distribution of the core. The strength distribution of the core is uneven because the relevant temperature distribution is much uneven. For example, although the strength of the core center

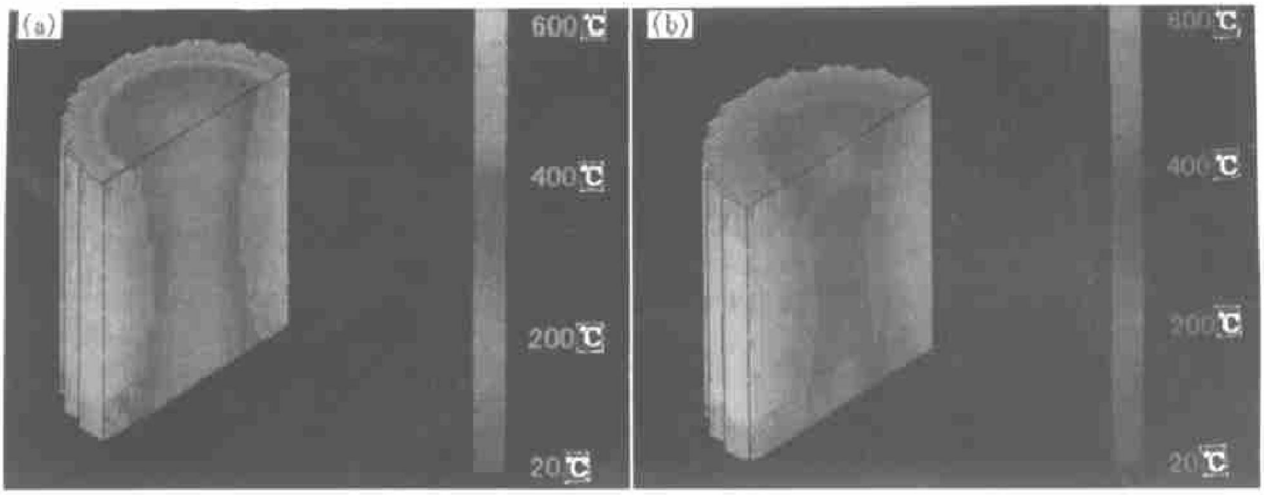

Fig. 1 Temperature distributions of core
(a) —t= 180 s; (b) —t= 400 s

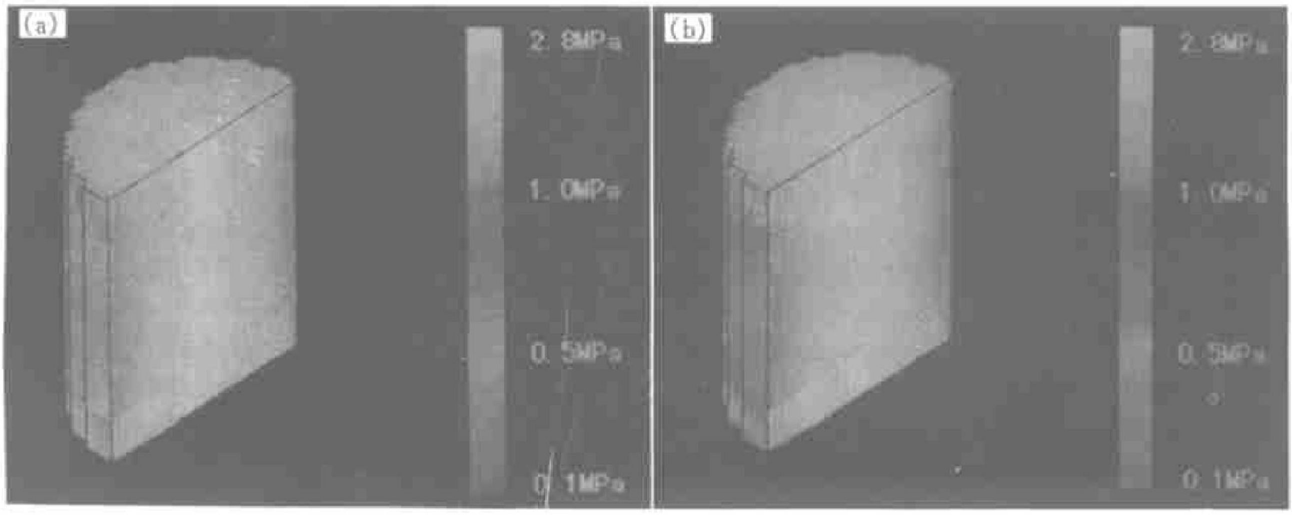

Fig. 2 Strength distributions of core
(a) —t= 180 s; (b) —t= 400 s

remained about 2.3 MPa, the strength of the core surface had dropped to about 0.6~ 0.8 MPa after the core was heated at 600 ℃ for 400 s.

In the present study, the heat transfer of a thin-wall aluminum alloy casting in resin sand mold is simulated. Fig. 3 shows the shape and dimensions of the casting and mold(core). The pouring temperature is 700 ℃. The molten metal is assumed to fill the mold instantaneously, and there is no temperature drop during the filling process.

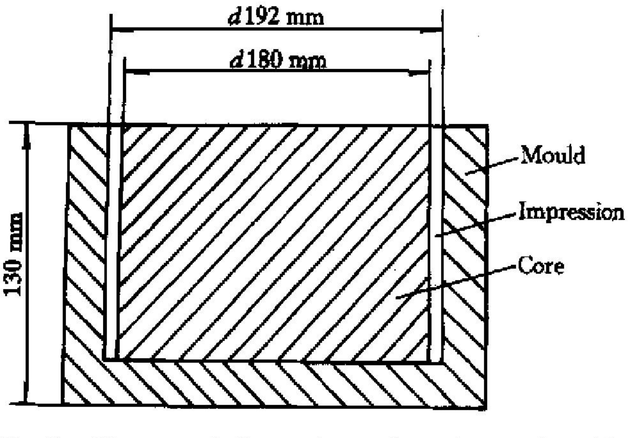

Fig. 3 Shape and dimensions of casting and mold

Fig. 4 indicates the simulated temperature distribution of the mold(core) during the solidification of the casting. Owing to the thinner casting wall and quick solidification of the casting, the heated extent of the mold(core) is small, which led only a thinner layer of the mold(core) to be heated to a higher temperature. Fig. 5 shows the simulated results of the strength distribution of the mold(core) after pouring 180 s. It shows that although the strength of the thinner layer of the mold(core) is dropped to below 1.0 MPa, the strength of the most parts of the mold (core) is higher and the relevant high-temperature retained strength of the mold (core) is higher also, which would result in the increase of the hot tearing tendency of the thin-wall aluminum alloy casting.

From the above results, the temperature and strength distributions of the mold(core) on heating can be quantitatively studied by using the self-developed simulation program , which lays a basis for the

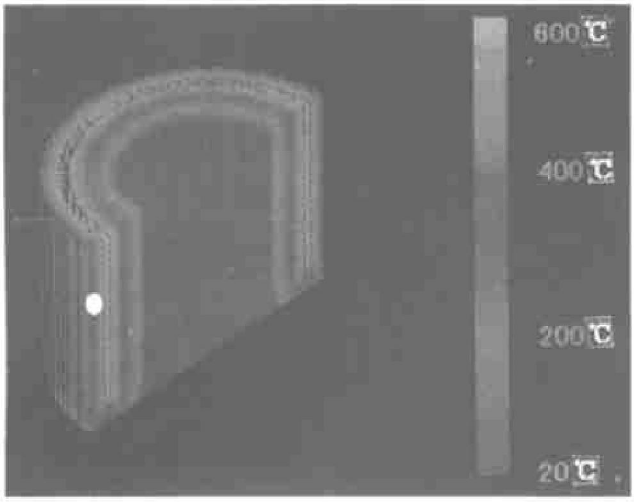

Fig. 4 Temperature distribution of mold($t = 180$ s)

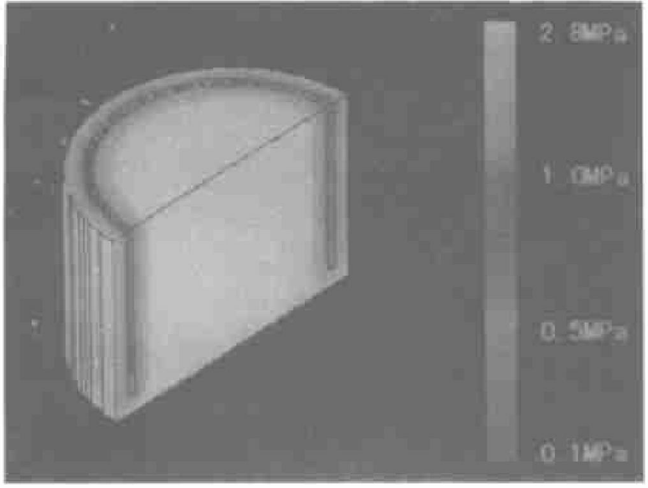

Fig. 5 Strength distribution of mold($t = 180$ s)

optimum design of the properties distribution of the mold(core) .

4 CONCLUSIONS

1) Numerical simulation software of the temperature and strength distributions of the mold(core) and relevant post-processing display software were developed by using Visual C++ and OOP technique. Utilizing the developed post-processing software, the graph color can be transferred smoothly and the temperature and strength distributions of mold(core) can be displayed visually and accurately.

2) The temperature and strength distributions of the mold(core) both in case of heating process for core in the furnace and solidification process for a thin-wall aluminum alloy casting in the mold(core) are uneven due to the lower thermal conductivity. Especially, in the solidification of the thin-wall aluminum alloy casting, only a thinner layer of mold (core) is heated to a higher temperature and the strength of mold(core) is lower.

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