Numerical simulation of thermal stress field for die casting dies of aluminum alloy①

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[Abstract] The thermal elastic-plastic constitutive equations suitable for computation of thermal stress of die casting dies were established. On the base of simulation of temperature field, the thermal stress field of die casting dies was simulated by COSMOS, and the effects of initial die temperature and coating on the surface of die on thermal stress distribution were studied. The results show that the thermal stress mainly concentrates on the die surface and the lower initial die temperature and no thermal resistance cause a higher thermal stress.

[Key words] thermal elastic-plastic constitutive equation; die casting dies; thermal stress

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1 INTRODUCTION

In die casting process, the dies experience a series of complicate changes. The temperature on the cavity surfaces of dies increases rapidly due to contacting and washing between the molten melt and dies, and the hot-yield strength in contact zone of the cavity is reduced rapidly. In the very thin layer of the die surface, thermal stress can exceed the yield strength of die material, resulting in plastic deformation[1~3]. The periodic temperature changes on the surfaces of the dies result in periodic thermal expansion, contraction and stress which causes thermal cracks. There were a few researches on thermal fatigue of die casting dies[1~8]. The relationship between die life and affecting factors was studied, such as casting operating conditions, chemical composition, heat treatment and surface treatment. But there were few researches on thermal stress of die casting dies. In this study, a thermal elastic-plastic simulation is proposed, enabling the periodic thermal stress of dies to be determined. It lays a foundation for the further study on thermal fatigue of die casting dies.

2 NUMERICAL SIMULATION OF TEMPERATURE FIELD

2.1 Pre-processing

Because solid modeling and enmeshing of complex casting and its dies are difficult, the accuracy and efficiency of computation are affected. It is significant to enmesh fast and precisely to coordinate the mathematical model with the enmeshing element of casting and dies, and to improve the level of the modeling software. This study adopts I-DEAS developed by SDRC Co. of American as pre-processing platform to accomplish solid model and enmeshment of casting and dies.

2.2 Numerical model of temperature field

The direct difference method was used to establish the numerical models of temperature field. The physical phenomena in each element may be directly expressed as difference equations that could be solved by computer. According to overall energy conservation, in a tiny time step Δt, the difference equation can be derived as

$$T_i^{t+\Delta t} = T_i^t + \frac{\Delta t \cdot \left[\sum_{j=1}^{n} \overline{\omega}(i,j)\left(T_j^t - T_i^t\right) + Q \right]}{(\rho C V)_i} \tag{1}$$

where

$$\overline{\omega}(i,j) = \frac{S_{(i,j)}}{R(i,j) + \dfrac{L_{(i,j)}}{\lambda_i} + \dfrac{L_{(i,j)}}{\lambda_j}} \tag{2}$$

$$R(i,j) = \begin{cases} 0 & \text{For the same material} \\ 1/h_{(i,j)} & \text{For different material} \end{cases}$$

$$Q = \Delta t \cdot \sum_{j=1}^{n} (\varepsilon \Gamma S)_{im} \left[\left(T_j^t\right)^4 - \left(T_i^t\right)^4 \right] \tag{3}$$

ρ is mass density, g/mm^3; C is specific heat capacity, J/(g·K); V is volume, mm^3; λ is heat conductivity, J/(mm·K); Δt is time step, s; T is element temperature, K; S is contacting area between two elements, mm^2; $L_{(i,j)}$, $L_{(j,i)}$ are interface distances from element i (j) to element j (i), mm; $h_{(i,j)}$ is convection heat resistance between element i and element j, J/K; ε is the radiation coefficient; Γ is Stepphen-Bolzman constant; n is the number of elements adjacent to the element i.

Eqn.(1) is derived from the heat energy conser-

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vation law, and the phase transformation and the influence of latent heat are not taken into account. The heat recover method is used in this study to treat latent heat released during metal solidification.

2.3 Stability condition

All elements of the casting and mold must satisfy critical time step of stability conditions for simulation system to avoid divergency of computation. The time step can be written as

$$\Delta t(i) \leqslant \frac{\rho(i)\ C(i)\ V(i)}{a_i} \tag{4}$$

where

$$a_i = \sum_{i-1}^{n} \omega(i, j) + \sum_{m=1}^{M} (\varepsilon \Gamma S)_m \cdot \frac{(T_i^t)^4}{T_i^t - 273.15} \tag{5}$$

3 NUMERICAL SIMULATING OF THERMAL STRESS FIELD

3.1 Nonlinear characteristics

For die materials, when the thermal stress in die casting dies caused by uneven temperature distribution exceeds the yield strength, the materials will step into the plastic state and the properties will change. The relation between stress and strain is not linear and the elastic matrix is not constant. The state of stress not only is related to strain, but also depends on the whole strain process. The thermal stress field of die casting dies can be computed with elastic-plastic method.

Another nonlinearity is geometric one caused by the effect of displacement on the overall geometric configuration of structure. During the calculation of thermal stress of die casting dies, the deformation caused by thermal stress changes results in corresponding variation on mesh grids. Since the deformation caused by thermal stress is quite small, the geometric nonlinearity may be neglected.

3.2 Thermal elastic-plastic constitutive equations

For thermal elastic-plastic theory, the strain increment can be written as[9]

$$\mathrm{d}\varepsilon_{kl} = \mathrm{d}\varepsilon_{kl}^{\mathrm{E}} + \mathrm{d}\varepsilon_{kl}^{\mathrm{P}} + \mathrm{d}\varepsilon_{kl}^{\mathrm{T}} \tag{6}$$

where $\mathrm{d}\varepsilon_{kl}$ is total strain increment, $\mathrm{d}\varepsilon_{kl}^{\mathrm{E}}$ is elastic strain increment, $\mathrm{d}\varepsilon_{kl}^{\mathrm{P}}$ is plastic strain increment, $\mathrm{d}\varepsilon_{kl}^{\mathrm{T}}$ is temperature strain increment.

If the effect of temperature on material constants, E and γ, is taken into account, elastic strain increment is written as

$$\begin{aligned} \mathrm{d}\varepsilon_{kl}^{\mathrm{E}} &= C_{ijkl}^{\mathrm{E}} \mathrm{d}\sigma_{ij} + \frac{\partial}{\partial T}(C_{klij}^{\mathrm{E}})\,\mathrm{d}T\sigma_{ij} \\ &= \mathrm{d}\varepsilon_{kl}^{\mathrm{E}'} + \mathrm{d}\varepsilon_{kl}^{\mathrm{T}'} \end{aligned} \tag{7}$$

where C_{ijkl}^{E} is elastic flexible tensor; $\mathrm{d}T$ is temperature increment; $\mathrm{d}\varepsilon_{kl}^{\mathrm{E}'}$, $\mathrm{d}\varepsilon_{kl}^{\mathrm{T}'}$ are elastic strain increments caused by changes of $\mathrm{d}\sigma_{ij}$ and C_{ijkl}^{E}, respectively, and

$$\mathrm{d}\sigma_{ij} = D_{ijkl}^{\mathrm{EP}}(\mathrm{d}\varepsilon_{kl} - \mathrm{d}\varepsilon_{kl}^{\mathrm{T}} - \mathrm{d}\varepsilon_{kl}^{\mathrm{T}'}) + \mathrm{d}\sigma_{kl}^{0} \tag{8}$$

The relation between stress and strain can be written as

$$\mathrm{d}\sigma_{ij}^{0} = \frac{D_{ijkl}^{\mathrm{E}}(S_{kl} - \overline{\alpha}_{ij})(\partial \sigma_{\mathrm{s}} / \partial T)\,\mathrm{d}T}{[2\sigma_{\mathrm{s}}(\overline{\varepsilon}^{\mathrm{P}}, M, T)/3](3G + E^{\mathrm{p}})} \tag{9}$$

where $\mathrm{d}\sigma_{ij}$ is thermal stress, $\mathrm{d}\sigma_{kl}^{0}$ is initial stress, D_{ijkl}^{E} is elastic matrix and D_{ijkl}^{EP} is elastic-plastic matrix, $\mathrm{d}\varepsilon_{kl}^{\mathrm{T}}$ and $\mathrm{d}\varepsilon_{kl}^{\mathrm{T}'}$ are regarded as initial strains and $(\partial \sigma_{\mathrm{s}} / \partial T)\,\mathrm{d}T$ caused by temperature is regarded as initial stress.

In this study, the FDM is used to simulate the temperature field. The temperature of element is represented by its barycenter. In the simulation of thermal stress field, the nodal temperature of element must be known. The temperature on node i is related to its environmental elements' temperature, and their contributions on nodal temperature are inverse proportion to the distances from barycenters of environmental elements to node i[10]. The node temperature can be obtained through calculation.

4 APPLICATION OF THERMAL STRESS FIELD

The thermal stress field of die casting dies was simulated by COSMOS. Temperatures on nodes can be directly transformed into heat loads. Fig.1 shows the thermal stress distributions of fixed dies. The effect of temperature on the yield strength of die material, H13, was taken into account and other thermal properties were considered to be constant for simplicity although they change with temperature.

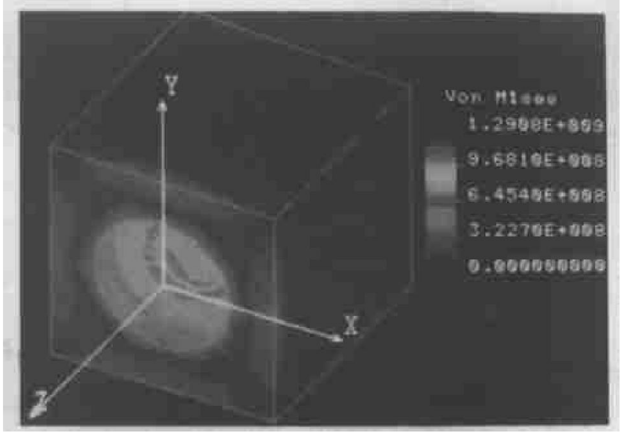

Fig.1 Thermal stress distribution of moving die insert
(t = 2.4 s; Initial die temperature = 473 K)

Fig.2 shows the sections of thermal stress distribution in fixed half of die. The simulation results indicate that thermal stress distribution is not uniform and mainly concentrates on the surfaces of cavity of dies and the geometric effect on thermal stress distribution is obvious. The thermal stresses near the cor-

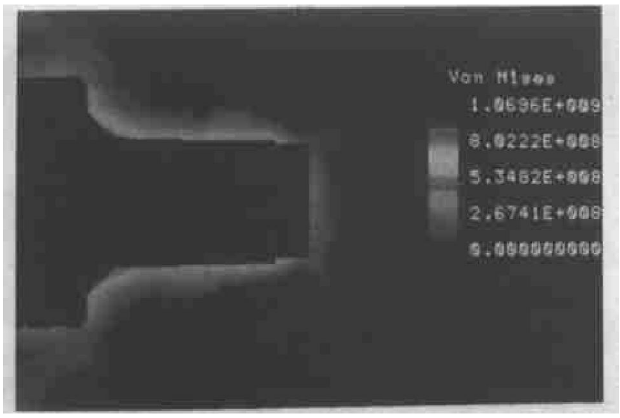

Fig.2 Section of thermal stress distribution
($t = 2$ s; Initial die temperature = 473 K)

ners in the die cavities become very high due to the geometric effects.

On the die casting production, the initial die temperature and coating on the surfaces of die are two important parameters. The effects of initial temperature and coating on the thermal stress were studied in this study. The 100 mm-long and 20 mm-thick runner was used for simulation. Fig.3 shows the stress distribution under different conditions. Because of high pressure and high liquid velocity, the coating layer may be washed off during die filling. Then, perfect contact between the liquid metal and die cavity can be assumed. Without coating, there is not thermal resistance layer between the molten aluminum and dies. The thermal stresses at and near die surface exceed yield strength, but at a distance about 4 mm below the surface, thermal stress is negligible. With an interface resistance layer, the thermal stress distribution is similar to that without interface resistance layer, but the highest stress is greatly decreased.

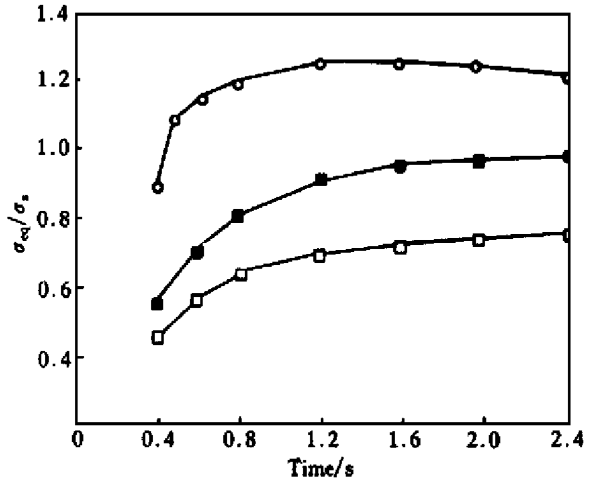

Fig.3 Thermal stress distributions at die surface under different conditions

□ —Initial temperature 473 K with thermal resistance;
■ —Initial temperature 293 K with thermal resistance;
○ —Initial temperature 293 K without thermal resistance

To find the effect of initial die temperature on thermal stress at the die surface, two initial die temperatures were examined. From Fig.3, it can be seen that the lower initial temperature results in a higher thermal stress.

In order to verify the simulation results, the residual stress distributions of a specimen were measured and compared with the simulation results. A bar specimen with length of 140 mm and diameter of 18 mm was heated by inductor and cooled by water. Starting from a uniform temperature of 20 ℃, the temperature of specimen surface can be rapidly heated to 473 ℃ in 5 s. The radial residual stress at the point with a distance of 3.5 mm below the surface of bar was measured by means of X2001-X-RAY stress analysis. The experimental measurement and simulated value of residual stresses are 117.3 MPa and 98.8 MPa, respectively. An agreement between the simulation results and experimental ones is reached.

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