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Control of deflection deformation of plate-shape castings in solidification①

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Abstract: The deformation mechanism during the solidification was analyzed based on the experimental results of the castings. An approximate quadratic differential equation and its discrete model of calculation deflection were proposed. The model indicates that the key factors leading to the deflection deformation are the thermal bending moment M and the flexural rigidity EJ. The smaller the former and the larger the latter is, the smaller the deflection deformation will be. The experiments are carried out at various technical conditions, and their results appear good agreement with calculation ones. A method was proposed to predict and control the casting deformation.

Key words: deformation; solidification; thermal bending moment; flexural rigidity
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1 INTRODUCTION

An order of large plate castings usually baffles the manufactures, as the deflection deformation is liable to occur during solidification of the castings. The common way to solve this problem is to pursue an optimum casting process route by trial and error method, or to keep larger machining allowance on the castings and machine away the deformed part subsequently, however, as a result, a higher casting cost is forced and the quality of casting is influenced directly.

The study on the modeling of casting deformation commences considerably late. After entering 1990s, the quantitative analyses of casting deformation have been developed by many researchers[1-6], as well as lots of fundamental experiments and technical amelioration for controlling deformation have been done[7-12].

In this paper, the deformation mechanism during solidification is analyzed based on the experimental results of the simplified plate-shape castings. And a mathematical model is proposed to predict and control the casting deformation.

2 EXPERIMENTAL

As shown in Fig. 1, the experimental apparatus consists of mould, pouring basin, displacement sensor and X-Y recorder etc. The steel plate was used as the bottom block, and the insulating brick as the mould wall. The quartz rod tip of the displacement sensor contacted the bottom block. The thermocouples were located in 1/4, 1/2, and 3/4 of casting height respectively. And the material used in the experiment is Al-4.5% Cu alloy. The casting was 20 mm in width and 30 mm in height, with a length of 300 mm. The width and height of casting could be altered according to the experimental requirement. This mould for beam-shape casting could be used to simulate the temperature and deformation of large plate casting in solidification because of its insulated wall.

During experiments, different thickness and temperature of the bottom block were chosen to convert the chill conditions. And different pouring temperatures were applied to investigate the effect of solidification time on the deformation. The measured results of temperature and deflection are shown in Fig. 2. and Fig. 3, where θ_J, θ_x, H_b are the pouring temperature, the temperature and the thickness of the bottom block respectively.

Fig. 2 and Fig. 3 indicate that the higher the pouring temperature is, the smaller the deflection would be. Fig. 3 also shows that the deflection is mainly developed during solidification process, not tightly associated with the subsequent cooling. Clearly, the deflection varies with different technological conditions. Moreover, the cross sections keep perpendicular to the axis before and after deformation, as well the elements between two cross sections are unchangeably parallel to the

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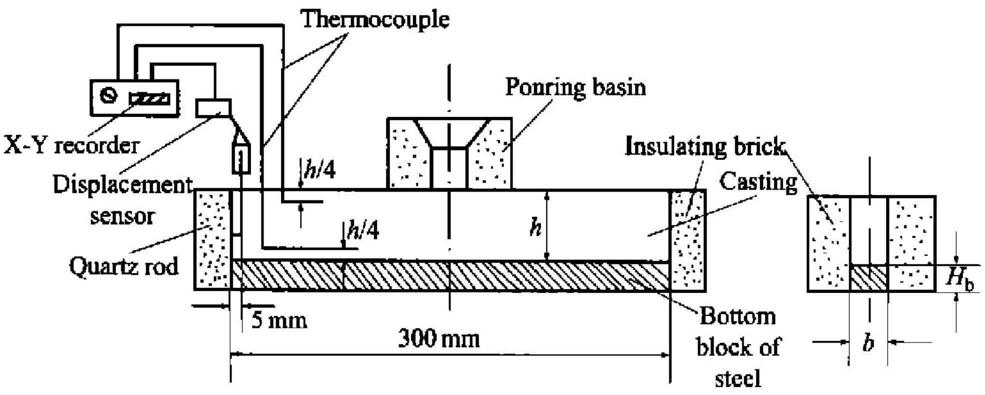

Fig. 1 Experimental apparatus

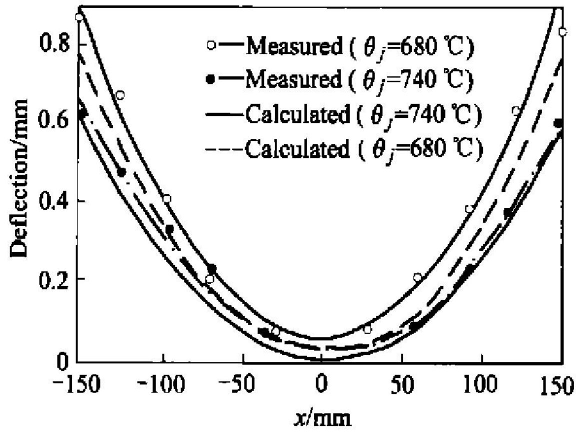

Fig. 2 Effect of pouring temperature on deflection

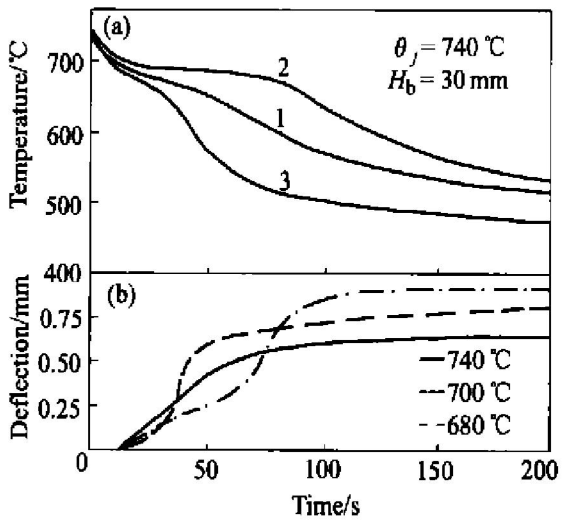

Fig. 3 Measured temperature and deflection during casting
(1 —Locate at $h/4$ to top;
2 —Locate at $h/2$ to top;
3 —Locate at $3h/4$ to top)

axis. The smooth parabolic curve of beam deflection shows the deformation is compatible.

3 MATHEMATICAL MODEL OF CASTING DEFORMATION

3.1 Basic assumptions

According to the results of deformation experiments, the following compatible assumptions of deformation are made:

1) The solidified layers of the beam casting consist of line bundles parallel to the axis and the bundles are only extended or shortened along the axis.

2) The bending deflection of solidified layers satisfies the plane assumption.

3) The deformation is a small one, and meet the superposition principle.

4) The material's properties are varied with temperature, as shown in Fig. 4.

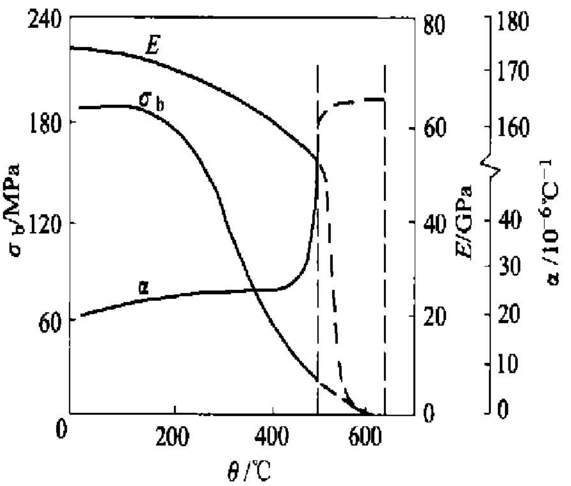

Fig. 4 Variation of material's properties with temperature

3.2 Mathematical model of bending deflection

Divide the beam casting into n small-segments, establish the coordinate system as Fig. 5 and select any segment $\Delta x_i = x_i - x_{i-1}$, apply incremental method, consider a piece of slice in the segment Δx_i with distance f from the axis and cross sectional area of df, whose temperature increment is $\Delta\theta = \theta_f^p - \theta_f^{p-1}$ during time interval $\Delta t = t^p - t^{p-1}$. According to assumptions 1) and 2), the stress —strain constitutive relation is

$$\Delta\sigma_f = E(\overline{\Delta x}/\Delta x_i - \alpha\Delta\theta) \quad (1)$$

where $\overline{\Delta x}$ is the mean linear shrinkage of the segment Δx_i, $\Delta\sigma_f$ is the stress increment acted on the slice df.

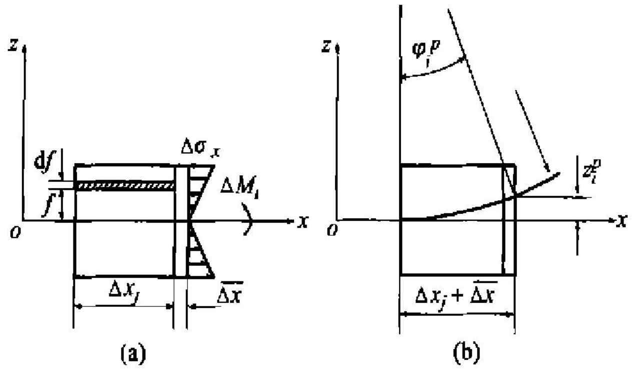

Fig. 5 Deformation of model of a segment

According to the equilibrium equation, we have

$$\int_F \Delta\sigma_x \mathrm{d}f = \int_F E(\overline{\Delta x}/\Delta x_i - \alpha\Delta\theta)\mathrm{d}f = 0 \qquad (2)$$

where α is the thermal expersion coefficient, 10^{-6} ℃$^{-1}$. Thus, the mean strain of the segment Δx_i is

$$\bar{\varepsilon} = \overline{\Delta x}/\Delta x_i = \int_F E\alpha\Delta\theta \mathrm{d}f / \int_F E\mathrm{d}f \qquad (3)$$

where F is the cross sectional area of segment Δx_i.

Eqn. (1) indicates that the uneven temperature increment $\Delta\theta$ results in non-uniform distribution of stress increments $\Delta\sigma_x$ in the cross section of the segment Δx_i, as shown in Fig. 5(a), so the segment Δx_i is subjected to a thermal bending moment as follows:

$$\Delta M_i = \int_F f\Delta\sigma_x \mathrm{d}f = \int_F E(\bar{\varepsilon} - \alpha\Delta\theta) f \mathrm{d}f \qquad (4)$$

As a result, the bending deflection takes place in the segment, as shown in Fig. 5(b), whose curvature is proportional to the thermal bending moment:

$$1/\rho = \Delta M_i / EJ_y \qquad (5)$$

where ρ is curvature radius, EJ_y is flexural rigidity. Since the deformation is small, the curvature equation is

$$1/\rho = \mathrm{d}^2 z/\mathrm{d}x^2 \qquad (6)$$

Combining Eqn. (5) and Eqn. (6), the differential equation of deflection curve is given by

$$\mathrm{d}^2 z/\mathrm{d}x^2 = \Delta M_i / EJ_y \qquad (7)$$

Integrating Eqn. (7) two times, the deflection curve equation is obtained, whose discrete model is

$$\varphi_i^p = \varphi_{i-1}^p + \Delta M_i \Delta x_i / EJ_y \qquad (8)$$

$$z_i^p = z_{i-1}^p + \varphi_{i-1}^p \Delta x_i + \Delta M_i (\Delta x_i)^2 / 2EJ_y \qquad (9)$$

where superscript p expresses the current calculating sequence in time, φ_i^p and z_i^p are the slopes of the deflection curve and the deflection at point x_i, respectively.

Eqn. (9) indicates that as Δx_i is small enough, the deflection curve is a quadratic parabola. Regarding the whole process of solidification and cooling, the slope and the deflection of deformation curve at point x_i are

$$\varphi_i = \sum_{p=1}^{k} \varphi_i^p \qquad (10)$$

$$z_i = \sum_{p=1}^{k} z_i^p \qquad (11)$$

where k is time interval number.

4 DISCUSSION

4.1 Effect of thermal bending moment

Eqn. (9) shows that thermal bending moment is the key factors leading to the deflection deformation. Eqn. (4) shows that the difference between the mean strain $\bar{\varepsilon}$ and the linear strain $\alpha\Delta\theta$ in the segment Δx_i is smaller, then thermal bending moment becomes smaller. That means, retarding the solidification and cooling process (e.g., increasing mold temperature or pouring temperature) will be effective to control the deflation deformation.

When other conditions are the same (pouring temperature θ_j = 740 ℃, the thickness of bottom block H_b = 25 mm), the changes of the deflection with different mould temperatures are shown in Fig. 6. The size of casting is 300 mm × 30 mm × 20 mm.

It shows that the higher the temperature of bottom block is, the slower the solidification process and cooling rate are, then thermal bending moment becomes smaller, and correspondingly the deflection would be smaller. It also indicates that the deflection takes place mainly at the end of the solidification and the cooling stage when casting temperature is still high. Thus, the deflection can be reduced using effective technological method to control this process.

4.2 Effect of flexural rigidity on deflection

The moment of inertia J of rectangular beam casting can be expressed as $J = bh^3/12$, so if the effect of the ratio of height to width of the beam casting on deflection could be comprehended, the effect of flexural rigidity EJ on deflection could be also clear.

Fig. 7 shows the forming process of deflection

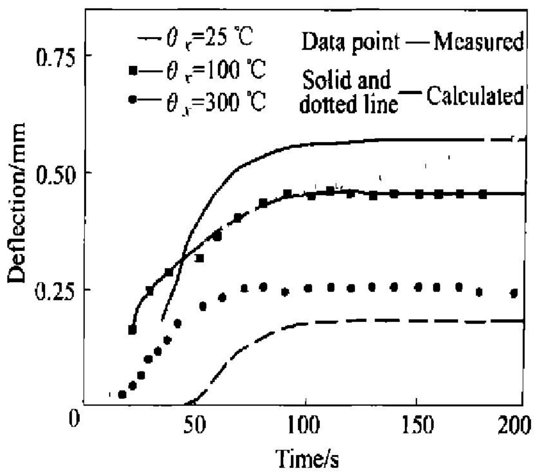

Fig. 6 Effect of temperature of bottom block on deflection

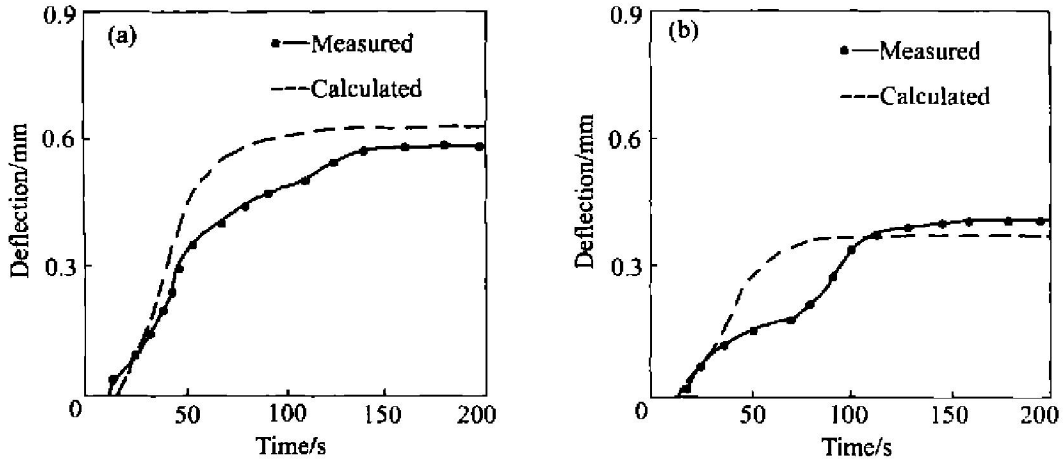

Fig. 7 Effect of ratio of height to width on deflection
(a) —h/b= 20/30; (b) —h/b= 30/20

of beam casting of Al-4.5%Cu alloy whose length is 300 mm, and cross section is 30 mm × 20 mm. In Fig. 7(a), h= 20 mm, b= 30 mm; in Fig. 7(b), h= 30 mm, b= 20 mm. Both the experiment and the calculated results show that the deflection is different greatly, as the ratio of flexural rigidity is large as 4∶9 in the two cases. The larger the flexural rigidity is, the smaller the deflection is. Accordingly, the ratio of height to width should be chosen to be greater than 1, that is, $h/b \geqslant 1$, which can reduce the deflection greatly. Therefore, as for plate casting, it is an effective method to increase the flexural rigidity greatly and reduce the bending deflection using vertical pouring to make the casting solidify sequentially from the bottom.

5 CONCLUSIONS

1) The mathematical model of deflection of beam casting is a quadratic equation of distance x. The deflection deformation is an accumulated value of quadric length from datum point to the end point, and can be predicted using numerical simulation.

2) The key factors leading to the deflection deformation are the thermal bending moment M and the flexural rigidity EJ. The smaller the former and the larger the latter is, the smaller the deflection deformation would be.

3) The thermal bending moment can be reduced by retarding the solidification process and the cooling rate, consequently reduces the deflection deformation.

4) As for plate casting, it is an effective method to increase the flexural rigidity greatly and reduce the bending deflection using vertical pouring to make the casting solidify sequentially from the bottom.

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