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ABSTRACT

A new method for mould filling calculation of lost foam casting (LFC) was developed based on the main hypothesis, which assumes that every point on the melt-pattern interface moves in the radial direction. The value of the normal velocity is calculated by an empirical formula, which is the function of the degree of vacuum, pattern density, pouring temperature, metallic static head, etc. At a given time step, every interface point moves to a new position, and all the points form the shape of the melt-pattern interface. Based on the new position of the interface and the given velocity of the interface cell, the fluid flow and the temperature distribution of the molten metal can be calculated during the mould filling process of LFC. The calculated results were validated by experiments.

1. Introduction

Numerical simulations have been successfully applied in conventional green sand casting, die casting, centrifugal casting, etc. However, the models of the mould filling and solidification in the lost foam casting (LFC) are still under investigation and the special software for the LFC process analysis is still under development [1,2].

During the mould filling process of lost foam casting, the violent physical and chemical processes occur between the molten metal and the polystyrene pattern [3,4]. Thus, the melt-pattern interface movement is different from conventional sand mould casting. Some researchers tried to calculate the mould filling process by exerting a hypothetical pressure or other restrictive conditions on the melt-pattern interface [5–8]. However, it is still very difficult to accurately deal with foam degradation, gas elimination, and pressure build-up in the mould during the mould filling process.

The basic strategy for the modelling of LFC is the 'backpressure' method. This method used the computational fluid dynamics technique (SOLA-VOF) to calculate the molten metal flow. However, during the metal filling process of LFC, there is polystyrene pattern ahead of the metal front, instead of the free surface (air) in conventional sand casting. To solve this, researchers tried to exert pressure onto the free surface to slow down the metal front advance. The pressure (backpressure) was calculated by the empirical formulas. Different researches developed different backpressure formulas. Zhou et al. [9] developed the InteCAST lost foam simulation software by considering the gas pressure impediment to the metal flow caused by pattern decomposition. The backpressure formula included the parameters of pattern density, pouring temperature, coating thickness, coating permeability, gas evolution, etc. Ohnaka et al. [1] calculated the gas flow inside the gap of the metal front, and the gas pressure was used as the boundary pressures for solving the melt flow. The backpressure formula took into account the overall heat flux from liquid metal to the pattern front by radiation, convection and conduction. Mirbagheri et al. [5] developed a model to calculate gas pressure at the melt/foam interface due to foam degradation. Different aspects of the process, such as foam degradation, gas elimination, and permeability of the refractory coating, were incorporated into the model. A computational fluid dynamics code was developed based on the SOLA-VOF technique for the simulation and prediction of the melt flow. Li et al. [10] studied the pyrolysis behaviour of the LFC foam patterns by using synchronous thermal analysis. The results showed that pyrolysis reactions involve physical and chemical changes in the decomposition layer of the LFC process. However, the results were not used to establish an empirical backpressure formula.

These different backpressure formulas stemmed from different experimental backgrounds and different hypotheses. The corresponding mould filling simulation conformed to the special experimental results. These calculations did not include the vacuum degree, which is a very important parameter in iron LFC production.

In this paper, a new method is proposed to calculate the locations of the melt-pattern interface according to the mechanism of the molten metal front movement during the mould filling process of LFC. Based on the calculated interface locations, the fluid flow and

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temperature distribution during the mould filling processes were calculated.

2. Physical model

The mould filling velocity and the shape of the melt front in LFC are quite different from the conventional empty mould casting. The velocity at the melt front is restricted by foam degradation, gas elimination, pressure build-up in the mould, etc. It is affected by the original process parameters, such as the degree of vacuum, the pattern density, and the metallic static head. The influence of the gravity on the mould filling velocity and the interface morphology in LFC is minor compared with conventional empty mould gravity casting [11]. According to the mechanism of the melt front movement during the mould filling process of LFC, a physical model of mould filling is proposed.

It is assumed that every point on the melt-pattern interface moves in a radial direction along the normal. This hypothesis is reasonable because the foam pattern vaporises under the heat of molten metal in a radial direction. The value of the normal velocity of cast iron is calculated by an empirical formula, which is the function of the degree of vacuum, pattern density, pouring temperature, metallic static head, etc. [12].

$$U = 661.967 + 153.96 \times vd - 0.7632 \times d + 0.8074 \times h - 0.940321 \times T + 0.0003397 \times T^2 \quad (1)$$

Here, U is an average filling speed (cm·s^{-1}), vd is the degree of vacuum (−MPa), d is the pattern density (g·l^{-1}), h is the down sprue height (cm), and T is the pouring temperature (°C). After a time step, every interface point moves to a new position, and all the points form the shape of the melt-pattern interface (Figure 1). It is also assumed that the sizes of down sprue and the ingates are large enough to ensure a choked gating system.

3. Numerical algorithm

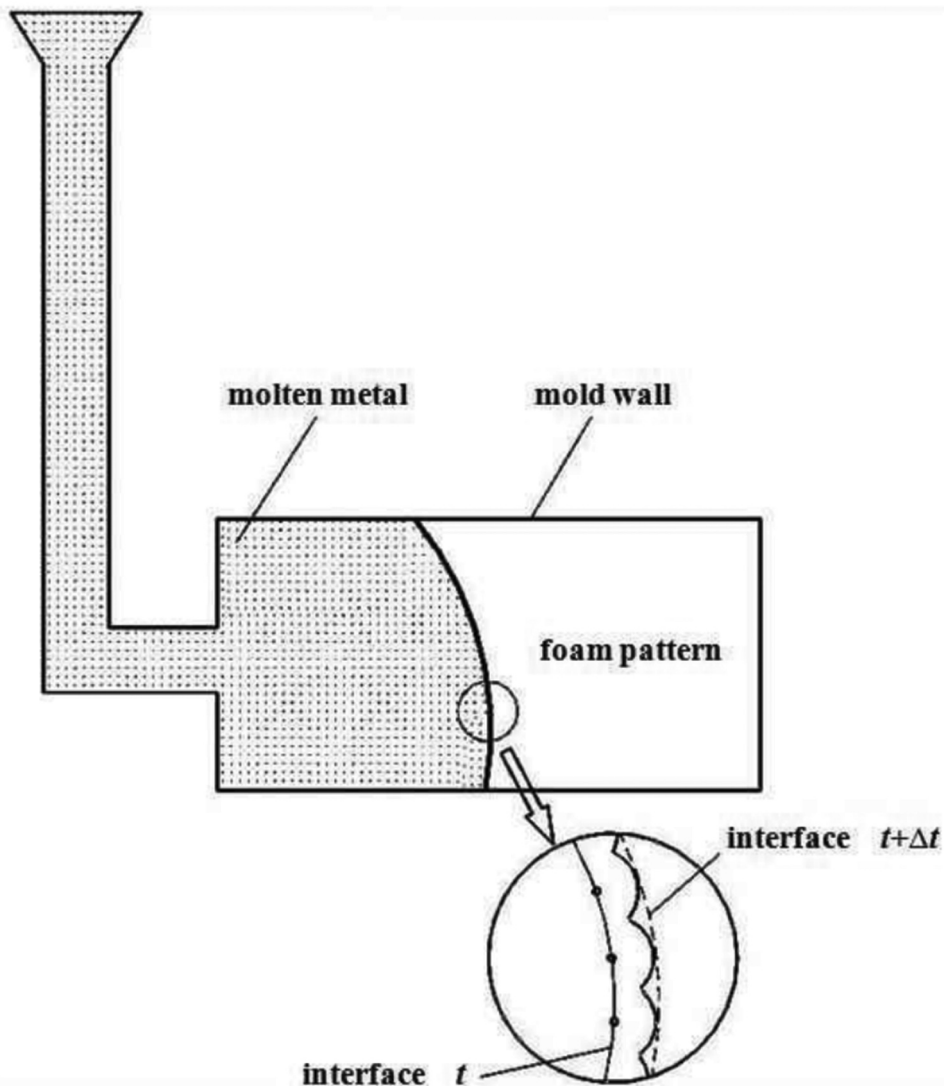According to the physical model, a numerical algorithm was developed. The casting (including the gating

Figure 1. Schematic diagram of the physical model of mould filling. Here, *t* is time.

system) is built into a 3D entity model by using the CAD software. Then the entity model is meshed to cubes with appropriate sizes by using the mesh software (Figure 2). These cubes are called cells. Each cell contains the information of its coordinate, edge length, filling conditions, filling speed, etc.

Every cell will have three kinds of possible filling conditions, full of molten metal (full cell), full of polystyrene pattern (empty cell), and partially filled with molten metal and partially filled with polystyrene pattern (interface cell). Full cells fill their adjacent empty and interface cells. The three kinds of orientations are all regarded as adjacent cells (Figure 3). In Figure 3, the shaded cubes represent the full cells.

In Figure 3(a), the full cell will fill its adjacent cell along the edge direction. At a given time step, the filling distance is calculated through multiplying the time step by the filling speed. The filling speed U is calculated using Equation 1). After some time steps, the accumulated filling distance reaches the value of the edge length (L); then, this adjacent cell is set to be a full cell and starts to fill its adjacent cells. In Figure 3(b), the full cell will fill its adjacent cell along the face diagonal line direction. When the accumulated filling distance
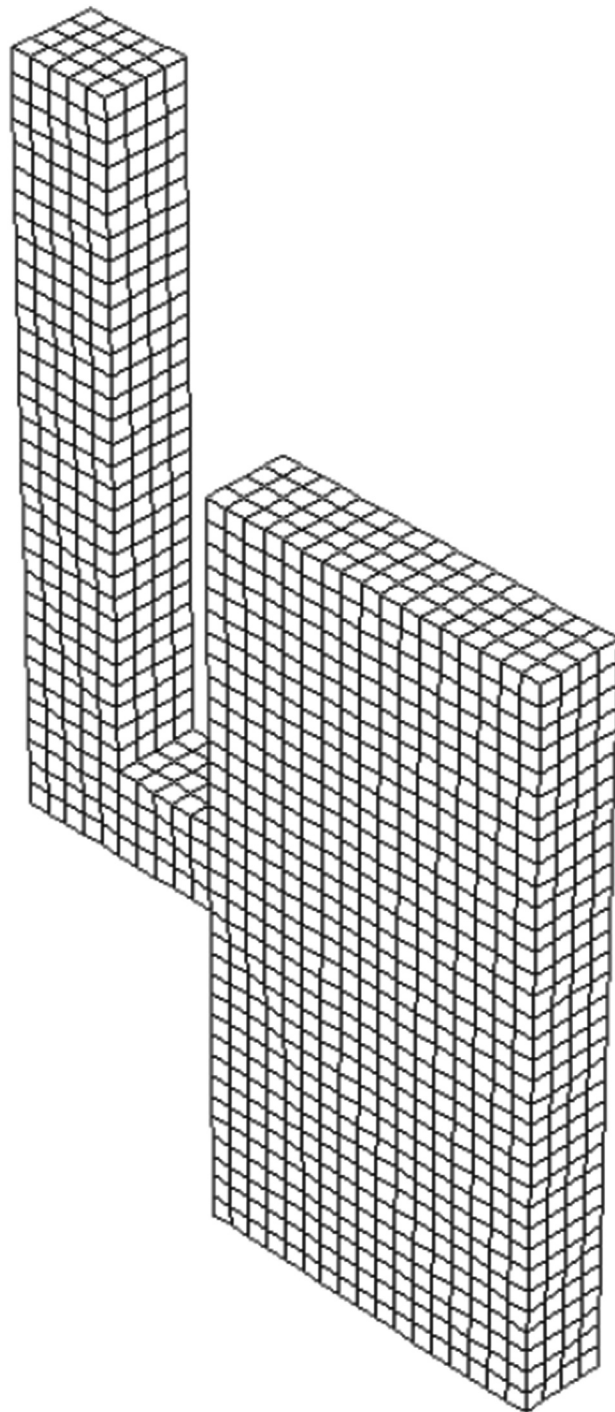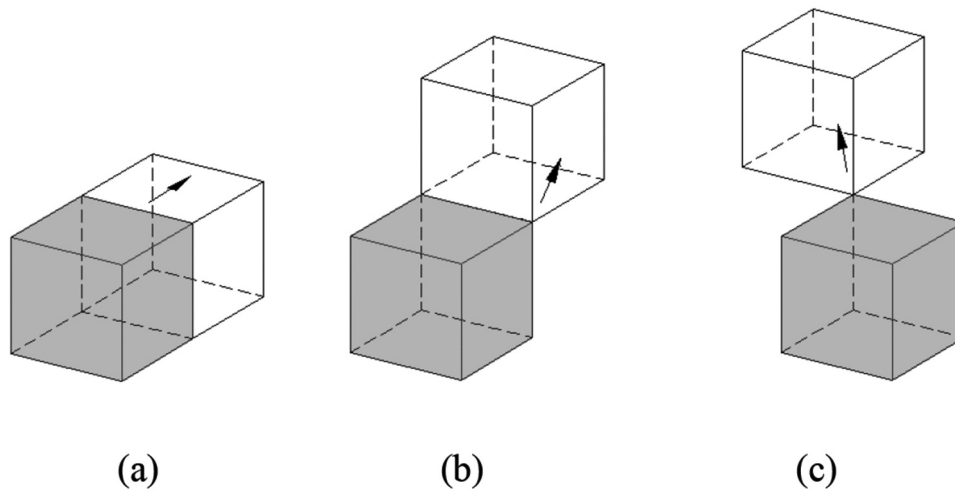

Figure 2. Meshed casting.

Figure 3. Three kinds of orientations of adjacent cells: (a) edge direction, (b) face diagonal line direction, (c) body diagonal line direction.

reaches the value of $\sqrt{2} \times L$, this adjacent cell is set to be full and starts to fill its adjacent cells. In Figure 3(c), the full cell will fill its adjacent cell along the body diagonal line direction. When the accumulated filling distance reaches the value of $\sqrt{3} \times L$, then this adjacent cell is full and starts to fill its adjacent cells.

According to this algorithm, the mould filling process calculation procedure is given below. The computer programming was done by use of the C++ computer programming language. In the program, the cell was defined as a 'class', which contained the variables of the coordinate, edge length, filling conditions, filling speed, etc. To begin with, the data of the coordinate and the edge length were read into a computer from the mesh file. Then the first layer cells (in Figure 1) were set to be full cells, representing the molten metal pouring from the top of the downsprue, while the other cells were set to be empty. By giving an appropriate time step, the calculation cycles began. For all the full cells, the computer searched their adjacent empty cells and interface cells. Then the filling distances of every adjacent cell were calculated according to the specific filling speed U. After some time steps, if the accumulated filling distances exceeded the characteristic values ($L, \sqrt{2} \times L$, $\sqrt{3} \times L$, respectively), then the corresponding cells were set to be full. In turn, these cells began to fill their adjacent cells. The calculation terminated when all cells became full.

4. Calculation of the fluid flow and temperature distribution

According to the above solution algorithm, the locations of the melt-pattern interface at any moment were obtained. The fluid flow and the temperature distribution during the mould filling can be calculated by solving the Navier-Stokes equation and the energy equation with the known computational technique.

The governing equations are expressed in the following general form:

$$\frac{\partial \varphi}{\partial t} + \frac{\partial}{\partial x_j}(u, \varphi) = \frac{\partial}{\partial x_j}\left(\Gamma \frac{\partial \varphi}{\partial x_j}\right) + S \quad j = 1, 2, 3 \qquad (2)$$

Here, φ is a dependent variable, t is time, x_j represents a three-dimensional coordinate component, u_j is a velocity component along the x_j-axis, Γ represents the diffusion coefficient and S is the source term. The equation represents the continuity equation, the Navier-Stokes equation, or the energy equation, when the dependent variable φ is 1, u_j or T (temperature), respectively. For a certain φ, there are corresponding Γ and S.

The fluid dynamics solution algorithm (SOLA) was applied to calculate the fluid flow in the Navier-Stokes equation [13]. The velocity boundary condition on the melt-pattern interface in LFC is different from the free surface in the conventional empty mould casting. In the lost foam casting, the melt front velocity is restricted by the evaporation velocity of the foam pattern. Thus, the melt front velocity could be set as the evaporation velocity of the foam pattern, and the direction is determined according to the relative orientation between the full cell and the filling cell.

The temperature boundary condition at the melt front in LFC is also quite different from the conventional empty mould casting. In the lost-foam casting, the melt front is remarkably chilled due to the evaporation and the decomposition of the foam pattern. Generally, some researchers used an equivalent heat transfer coefficient to deal with the chilling effect [8,11]. In this paper, the boundary conditions are treated by providing the heat transfer rate between the molten metal and the pattern.

5. Experimental verification and applications

Based on the above algorithm and the numerical technique, a computer program module was developed. The program module can calculate the melt-pattern

interface motion along with the velocity and temperature fields. The module was integrated into the casting simulation software that includes solid geometry modelling, mesh generation, displaying results, and the physical parameter database, etc. The necessary parameters, such as the degree of vacuum, pattern density, pouring temperature, materials, ambient temperature, etc., can be input into the computer program through an interface. Then the calculations run automatically and the computer outputs the results into the files.

A vertical plate-like iron casting was poured to test the results of the calculated interface location. The profiles of the molten metal front at different times were measured. The experimental procedure was described in reference [12]. In this experiment, pattern density, pouring temperature, vacuum degree and pattern thickness are 13.2 g·l^{-1}, 1400°C, −0.047 MPa, and 20 mm, respectively. The calculation is based on the data in Table1.

Both simulation and experimental results shown in Figure 4 demonstrate typical characteristics of the radial interface movement in LFC, and the melt in the lower part

Table 1. Vertical plate-like iron casting LFC simulation data.

| Property	Value
Material: Cast iron (wt.%)	C: 3.25, Si: 1.95, Mn: 0.9, Cr: 0.28, Cu: 0.35, S: 0.08, P: 0.05.
Density (g·cm^{-3})	7.18 (Cast iron liquid), 2.8 (Sand).
Thermal conductivity (cal·(s·cm·°C)$^{-1}$)	0.076 (Cast iron), 0.0036 (Sand).
Specific heat capacity (cal·(g·°C)$^{-1}$)	0.195 (Cast iron), 0.18 (Sand).
Latent heat (cal·g^{-1})	56.08
Viscosity (cm^2·s^{-1})	0.04
Transformation temperature (°C)	T_L: 1224, T_S: 1115.
Interface heat transfer coefficient (cal·(s·cm^2·°C)$^{-1}$)	0.0179
Sand temperature (°C)	25

(a)

(b)

(c)

(d)
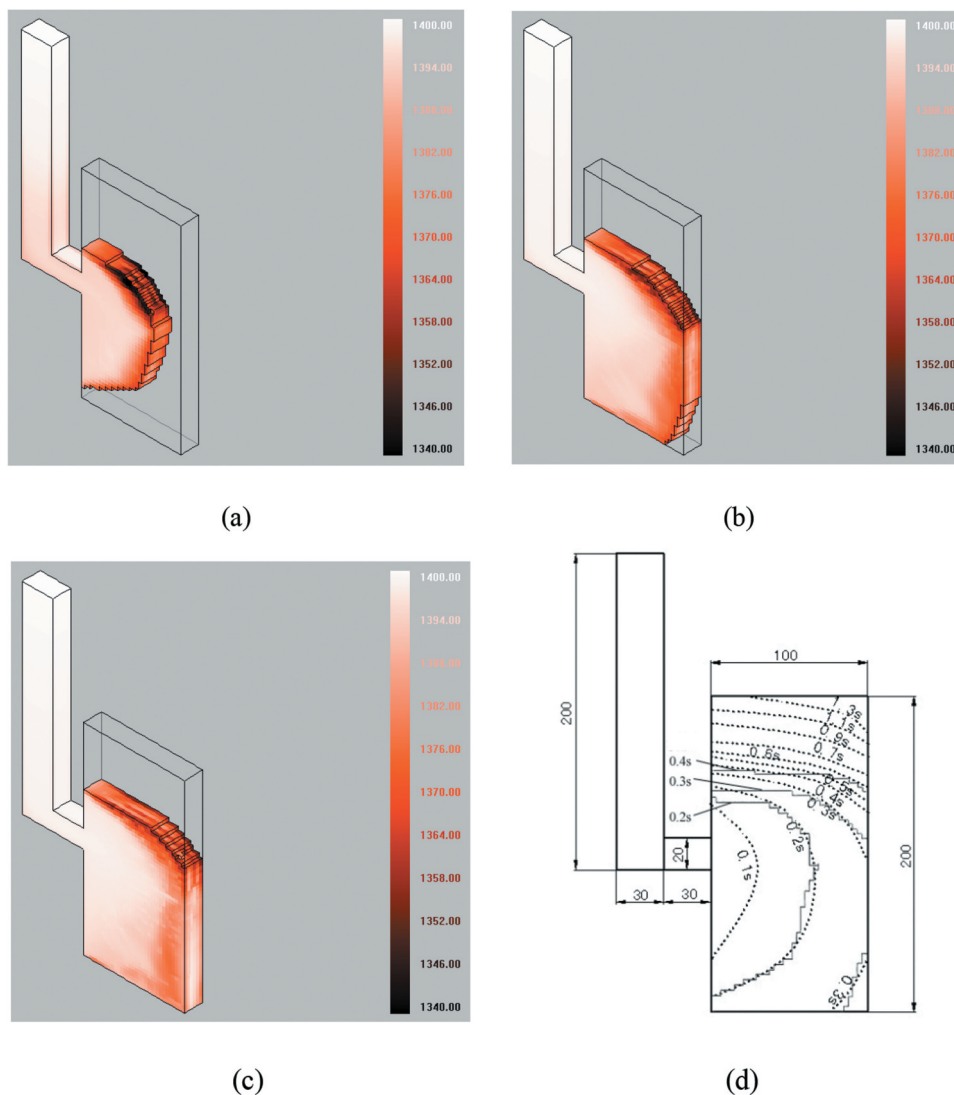
Figure 4. Comparison of simulation and experimental results of a lost foam plate casting. (a) simulation 0.2 s, (b) 0.3 s, (c) 0.4 s (the temperature unit is °C), (d) experiment (dotted line is an experiment, and solid line is a simulation. Dimensions are in mm.

of the filling region moves quicker than the upper part because of the different metallic static head. The simulation results at different times in Figure 4(a-c) are consistent with experiments in Figure 4(d) in terms of both the melt front profile and filling sequences. At 0.2 s time, the measured horizontal filling distance from the gate is 67.6 mm, and the simulation result is 71 mm. This deviation is acceptable for practical applications. The simulation results also indicate the chilling phenomenon at the melt front.

The software developed was successfully applied to optimise the casting design of the lost-foam ductile iron hub casting. The mould filling simulation showed that the chilled melt front would encounter at the opposite side of the gate, as shown in Figure 5(a). Because of the chilling phenomenon at the melt front during the mould filling, defects would occur with high probability at this location. This was validated by the trial pouring in Figure 5(b). Thus, a slag-remove-riser should be designed for the overflow of the chilled melt (Figure 6).

(a)   (b)

Figure 5. Mould filling simulation showing the chilled melt front (the units are °C) (a) and the corresponding defect of a lost form hub casting (b). The material is ductile iron 65–45–12 and the pouring temperature is 1450°C.
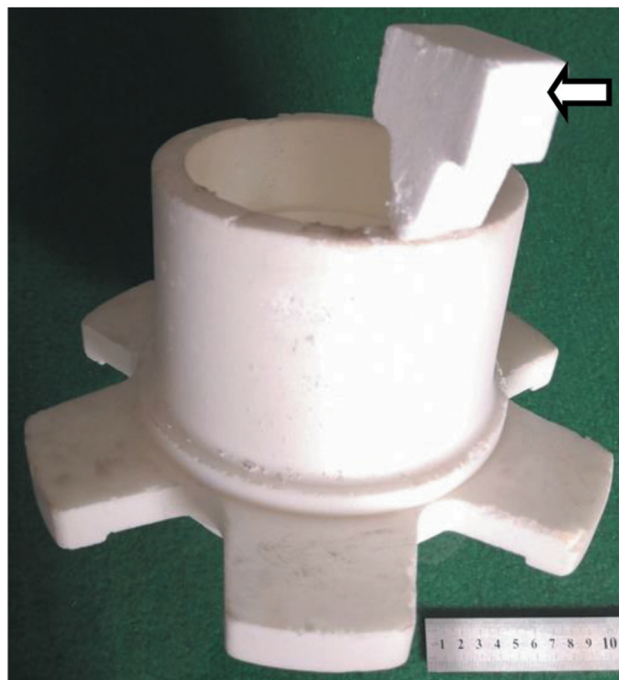
Figure 6. The slag remove riser.

6. Conclusions

(1) Based on the mechanism of the foam pattern vaporisation under the heat of molten metal, it can be assumed that the melt-pattern interface moves in a radial direction along the normal. The value of the moving speed is calculated by the empirical formula. According to these, the locations of the melt-pattern interface during the mould filling in LFC can be calculated by the developed numerical algorithm. The calculated results are consistent with the mould filling tests.

(2) According to the known locations of the melt-pattern interface and the special boundary conditions, the fluid flow and the temperature distribution during the mould filling process can be calculated by the numerical solution of the Navier-Stokes and energy equations. The simulation results can be applied for casting design optimisation and defects prevention.

Disclosure statement

No potential conflict of interest was reported by the authors.

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