Diagnosis parameters of mold filling pattern for optimization of a casting system

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Abstract: For optimal design of a gating system, the setting of diagnosis parameters is very important. In this study, the permanent mold casting process was selected because most of the other casting processes have more complicated factors that influence the mold filling pattern compared to the permanent mold casting process, such as the surface roughness of mold, gas generation from the mold wash and binder of sand mold, and the gas permeability through a sand mold, etc. Two diagnosis parameters (flow rate difference and arrival time difference) of molten metal flow pattern in the numerical simulation are suggested for design of an optimum casting system with a permanent mold. The results show that the arrival time difference can be used as one important diagnosis parameter of the complexity of the runner system and its usefulness has been verified via making aluminum parts using permanent mold casting (Fig. 9).

Key words: mold filling pattern; optimum casting system; diagnosis parameter; permanent mold casting process


Numerical simulation is one of the most effective methods to observe the mold filling pattern of the molten metal. Recently, the optimum casting system design module has been developed based on the numerical simulation of mold filling pattern, and a few research results have been reported. In these studies, however, the flow pattern judgment criteria have not been clearly defined, and many casting system decisions are made purely by the experts' subjective opinion.

Many studies using numerical simulation methods and optimization algorithms have been carried out in order to obtain optimal casting systems. In the U.S., Prof. J. A. Dantzing's research team from University of Illinois studied how to connect solidification simulation with mathematical optimization technique [1], which led to study of how to remove micro-defects inside castings. In Germany, Prof. P. R. Sahm's research team from Aachen Tech. Casting Research Center studied how to automate the casting optimization process [2]. The software has been developed to decide the optimum casting design such as size and location of a riser and pouring temperature, if the mechanical properties of the end product were designated [3]. However, most of these studies are concerned with the solidification processes of casting. The defect criterion related to the mold filling processes of castings has not yet been well developed.

The permanent mold casting process was selected in the present study, because most of the other casting processes have more complicated factors that influence the mold filling pattern compared to the permanent mold casting process, such as the surface roughness of mold, gas generation from the mold wash and binder of sand mold, and the gas permeability through a sand mold, etc. Also the permanent mold casting process is widely applied in producing parts for automobile industry, ship industry, construction industry, and so on.

In this study, two diagnosis parameters (the flow rate difference and the arrival time difference) of molten metal flow patterns in the numerical simulation are suggested for design of an optimum casting system with the permanent mold; and their usefulness has been verified as well via making aluminum parts using permanent mold casting (Fig. 9).

1 Numerical method

1.1 Governing equation

In this study, the two phase flow numerical model, which has an immiscible interface within the 3-dimensional, unsteady, and incompressible Navier-Stokes equation, was considered.

\[
\frac{\partial}{\partial t} \rho(u + \nu \cdot \nabla u) = -\nabla p + \mu \nabla^2 u + \rho g + F_s
\]

where \( F_s \) stands for body forces, \( g \) for gravity and \( t \) for time. \( \mu, \rho, u \) and \( p \) represent the dynamic viscosity, the density, the velocity of fluid flow and the pressure, respectively.

The hybrid scheme was used to increase calculation accuracy on the convection term. The convection term of the Navier-Stokes equation was discretized into the central...
difference and the upwind difference in a staggered grid system. The two difference equations were combined into the hybrid difference type.

1.2 Stable calculation condition

In the case of SOLA-VOF \(^{(4)}\) that is calculated by the upwind scheme, there happens to be vibrations and divergence values in time and space. This is called numerical instability and it brings many numerical errors and can have physically unallowable values. Not to generate these unstable values, the time step considering control volume size and stable condition has to be set up and on time march as follows. First, the fluid cannot move more than a cell per one time step because the flux terms of the finite difference equation only approximates its own cell. Second, if the diffusion number condition is analyzed based on the linear stability analysis, the time step can be shown by the following equation.

\[
\delta t < \frac{1}{2v} \frac{\delta x^2 \cdot \delta y^2 \cdot \delta z^2}{\delta x^2 + \delta y^2 + \delta z^2}
\]

(2)

In this calculation, the minimum time step control condition is used while the stable numerical calculation is kept.

2 Results and discussions

2.1 Analysis of numerical simulation results

To develop the diagnosis parameter of flow pattern, a simple plate type model with a thin flat wall was chosen, as shown in Fig. 1. Usually, shrinkage defects in thin sections are relatively rare; while casting products with thick walls have the shrinkage defects concerned with the solidification.

In this study, eight kinds of in-gate systems were suggested for the comparison of molten metal filling patterns according to the in-gate position changes. (See Fig. 2.)

![Fig. 1: Schematic diagrams of thin flat wall plate](image1)

**Fig. 1: Schematic diagrams of thin flat wall plate**

**Fig. 2: Eight kinds of in-gate systems**

![Fig. 2: Eight kinds of in-gate systems](image2)

There are many parameters that can be used as criteria of an ideal flow pattern such as flow rate, arrival time difference of runner system, and collision of free surface and vortex shedding. Here two kinds of parameters have been considered. One parameter is the flow rate difference. Volume flow rate is calculated as the fluid volume passing through an in-gate in a unit time. It is usually represented by the symbol \(Q\). Given an area \(A\), and a fluid flowing through it with uniform velocity \(v\), an angle \(\theta\) away from the direction perpendicular to \(A\), the flow rate is:

\[
Q = A \cdot v \cdot \cos\theta
\]

(3)

Here the flow rate of each in-gate was measured five times (when 40, 50, 60, 70, and 80% through the flow process), after that an average flow rate was calculated from those five measured values. Also by subtracting the minimum value from the maximum value, a flow rate difference for each runner system was calculated.

The other parameter is the arrival time difference. To see the complexity of the runner system, the molten metal arrival time at each in-gate was considered. By subtracting the first arrival time from the last arrival time, the arrival time differences can be obtained, which is convenient to decide whether the runner system is too complicated or not.

The five in-gates have been identified in five line types as shown in Fig. 3. Figure 4 is the results of numerical simulation.

![Fig. 3: Line type identification of five in-gates](image3)
From the results above, it can be found that the runner system with two in-gates in case 7 has the most ideal results with both a minimum value of flow rate difference and arrival time difference. For the runner system with five in-gates in case 8, at first the flow rates of all five in-gates show a slightly different gradient. Then the flow time goes on for longer, the difference of flow rate becomes smaller with a similar gradient. So in this study, the gating systems in both case 7 and case 8 are considered as candidates for sound gating system.

### 2.2 Analysis of experimental results

Figure 5 shows a water analogue test model which was used to investigate the flow pattern in a cavity and to allow comparison with the numerical simulation results.

The filling situations of casting cavity (with five in-gates) at different times are shown in Fig. 6. In Fig. 6, there is a good agreement between numerical and experimental results, but the final filling time difference between simulation and experiment was about 1.2 s. The flow pattern of molten metal is captured precisely by the numerical method. It is shown that the molten metal tends to rush to the opposite side wall after entering the cavity; then those five streams meet with each other and flow to the lower right side; after reaching the lower right corner, they rush backward.

The molten metal passing through in-gates Nos. 1 and 5 fills the cavity more rapidly than the fluid passing through in-gates Nos. 2, 3 and 4. (The in-gate number is the same as shown in Fig. 3.). This happens due to flow rate difference between the in-gates.

In the case of the two in-gates system shown in Fig. 7, it also shows good agreement between the simulated and experimental results. There is a little filling time difference between the simulation and experiment while the above five in-gates system case shows a 1.2 s filling time difference.

In this case, the molten metal fills the cavity (with two in-gates) from the lower right corner to the upper left corner, while the molten metal fills from upper left corner and rushes backward after reaching the lower right corner in the case with five in-gates. The two layer flow (see Fig. 8) in the case in five in-gates could cause mixed oxides in the cast products and bad influences on the mechanical properties.

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**Fig. 4: Results of numerical simulation for different cases**

![Flow rate vs. Flow time graphs for different cases](image)

**Fig. 5: Assembled transparent mold**
Fig. 6: Results from the gating system with five in-gates

Fig. 7: Results from the gating system with two in-gates

Fig. 8: Two layer flow
2.3 Actual casting experiments

In order to verify the numerical simulation and water experiment results, real aluminum parts were made by using permanent mold casting (Fig. 9).

Figure 10 shows two aluminum castings from the runner systems with two and five in-gates. From this comparison of results, as one can see, the runner system with two in-gates suggested by the numerical simulation results is a sound gating system.

3 Conclusion

In this study, two diagnosis parameters of molten metal flow pattern in the numerical simulation are suggested for design of an optimum casting system with the permanent mold. One is the flow rate difference and the other is the arrival time difference. The arrival time difference can be used as the diagnosis parameter of the complexity of the runner system.

References


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