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Technical Paper

Improved filling condition to reduce casting inclusions using the submerged gate method

Tingli Wang [a,b], Shan Yao [a,*], Qiang Tong [a], Longfei Sui [a]

[a] *School of Materials Science and Engineering, Dalian University of Technology, Dalian, China*
[b] *Dalian Bingshan Metal Technology Co., Ltd., Dalian, China*

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ABSTRACT

The submerged gate filling processes were investigated through the use of particle image velocimetry (PIV) measurements, numerical simulation and castings production. The results showed that the submerged gate filling can improve the mold filling conditions, which may reduce the occurrence of inclusion defects during casting production. The liquid free surface in the mold rose slowly and smoothly during the filling process, which could reduce the occurrence of oxide film inclusion defects. The flow velocity decreased from the gate to the mold, which may reduce the severity of the liquid impingement that causes sand wash defects. The liquid flow inside the mold, with the exception of the flow path region, was primarily quiescent and the distance from the submerged gate to the free surface was relatively small. Therefore, low density slag in the liquid could be carried to the liquid free surface by the fluid flow and by the slag's buoyancy.

1. Introduction

Inclusion defects caused by oxide film presence, sand washing and low density slag formation are common in the casting process and can significantly degrade a casting's mechanical properties. The industry consensus is that the filling process is crucial to casting quality and that most casting scrap arises from the few seconds in which the castings are poured [1]. Inclusion defects are significantly affected by the free surface condition, gate velocity and the flow distribution during the filling process. The filling system performs a very important role in controlling inclusion defects. It has been demonstrated that a poorly designed filling system often results in high flow velocity and surface turbulence. Cox et al. compared the effects of top and bottom filling systems on the quality of castings, and found that the bottom filling method had a smooth free surface which was beneficial to reducing film inclusions for large castings [2]. These findings were also supported by Dai et al. found that inclusion defects were significantly affected by the gate velocity during the mold filling process [3]. Liu et al. studied the characteristics of filling processes in low pressure castings. Their results showed that the free surface would rise as a jet and cause inclusion defects if the gate velocities were high [4]. These findings infer that the flow condition near the gate is the key factor affecting inclusion defects.

The water modeling method has been used extensively to study liquid metal flow conditions because the kinematic viscosities of liquid metals and water are nearly same, and water is easier to work with and visualize. With the development of particle image velocimetry (PIV) technology, it has been applied to measure both the instantaneous velocity and related properties in the fluid. Deng et al. studied the effect of nozzle shape on surface fluctuations in high speed continuous casting molds using the water modeling method. Their results showed that fluid flow in the mold had a well-defined symmetrical distribution by well-bottom and flat-bottom submerged entry nozzles [5]. Thomas et al. used PIV to evaluate the fluid velocity in a continuous slab casting mold and found that PIV was both useful and practical for measuring the flow velocity [6]. Chiu et al. used the PIV, shadowgraph technique and a thermochromic-liquid-crystal slurry to investigate the flow development during solidification of $NH_4Cl–H_2O$, results revealed that the filling-box process originated from the bottom to the top, which would cause V-segregation [7].

Numerical simulation methods have been extensively applied to study inclusion defect formation mechanisms. These numerical methods are quantitative, intuitive and concrete and are very practical for analyzing filling process characteristics and inclusion defect formation in detail. Melendez et al. developed a model for predicting the growth and motion of oxide inclusions during the

* Corresponding author.
E-mail address: yaoshan@dlut.edu.cn (S. Yao).

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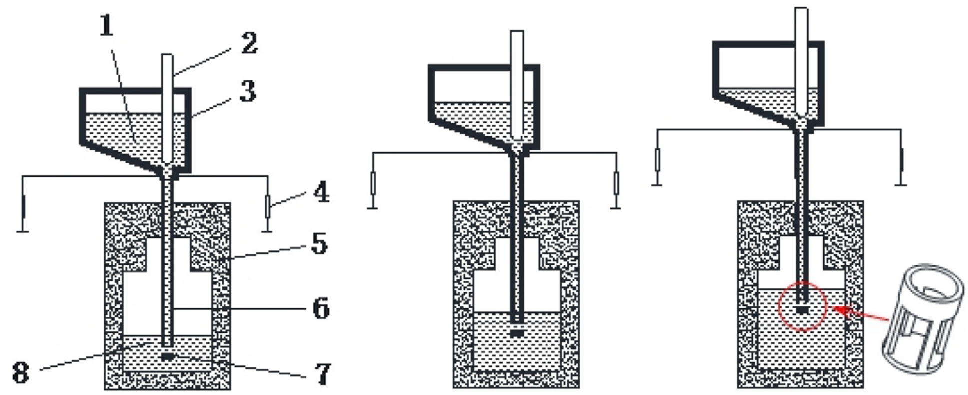

Fig. 1. Schematic diagram of the submerged gate filling process. 1-Liquid in tundish, 2-Stop rod, 3-Tundish, 4-Elevator, 5-Mold, 6-Sprue, 7-Diverter, 8-Poured liquid.

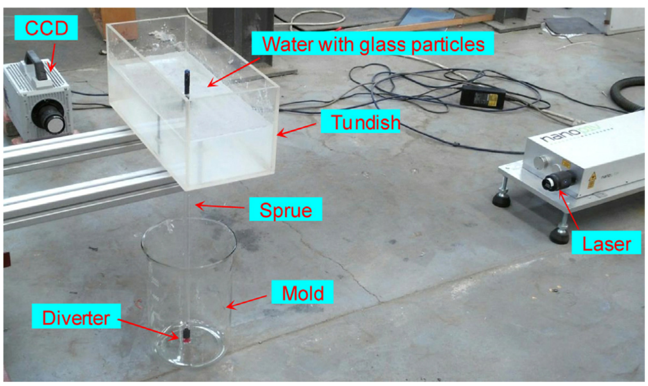

Fig. 2. PIV device used for measuring the flow distribution.

pouring process and determining their final locations on the surface. Their numerical simulation results showed that the inclusion's motion was controlled both by buoyancy and the liquid drag force. This provided a quantitative method for studying the formation of inclusions [8].

These previous experimental and analytical studies investigated the mold filling process and to some extent revealed the nature of inclusion formation mechanisms. However, most of these studies were limited to conventional casting methods. Submerged gate filling is a new method that has the potential for producing high quality castings. In contrast to conventional casting methods, the gate is submerged below the free surface of the liquid during the mold filling process. The gate can be moved vertically in synch with the rising of the free surface of the mold liquid by using an automated mechanical system, as is shown in Fig. 1. Controlling such a system was discussed in our previous study [9]. To study the characteristics of the submerged gate filling process, this paper was specified in the following aspects: the fluctuation and rise velocity of the free surface in the mold, the flow distribution from the gate to the mold and the trajectories of the low density slag. Additionally, the effects of the submerged gate filling method on reducing the inclusion defects in castings were analyzed.

2. Materials and methods

In this study, PIV method was used to measure the flow distribution during the filling process, as shown in Fig. 2. To achieve good PIV measurement resolution, both the tundish and the mold were made of glass or perspex. Silvered hollow glass particles with a density of 1.050 g/cm^3 and an average diameter of 40 μm were used as seeding. These particles had good light scattering property and could follow the flow dynamics accurately, which was beneficial to calculate the flow speed and direction exactly. A flat-walled diverter was installed below the gate in the submerged gate filling process.

Table 1
The initial conditions and boundary conditions for the numerical simulation.

No.	Property	Parameter
1	Internal radius of the submerged sprue	5 mm
2	Length of the submerged sprue	400 mm
3	Internal radius of the mold	90 mm
4	Height of the mold	200 mm
5	Submerged distance	20 mm
6	Flow velocity at the gate	2 m/s
7	Filling time	25 s
8	Liquid material for filling	Water

Numerical simulation of the mold filling process was performed using COMSOL Multiphysics, a software package that is based on the finite element method. The initial conditions and boundary conditions for the numerical simulation are shown in Table 1.

The flow equations were only solved in two dimensions because the model was axisymmetric. To evaluate the filling process, the following flow equations were used:

Continuity equation (mass conservation):

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

Momentum conservation equations (Navier-Stokes equations):

$$\rho(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y})=-\frac{\partial P}{\partial x}+\rho g_x+\mu\nabla^2 u \quad (2)$$

$$\rho(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y})=-\frac{\partial P}{\partial y}+\rho g_y+\mu\nabla^2 v \quad (3)$$

In the above equations, u and v are the velocity components in the x and y direction, respectively; ρ is the fluid density; P is the pressure; g is the gravitational acceleration; μ is the fluid viscosity; and ∇ is the Laplacian operator.

As a part of this study, the aluminum alloy prototype castings were produced using the top filling and submerged gate filling methods. Liquid aluminum alloy was poured into a mold at 700 °C with some inclusions purposely introduced.

3. Simulation and experimental results

3.1. PIV measurements results

During the top filling process, the free surface of liquid in the mold was not smooth. The surface of the liquid already poured into the mold was constantly agitated by the new liquid being