Mold Filling Analysis in Lost Foam Casting Process for Aluminum Alloys and Its Experimental Validation

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A mathematical model is developed in this study to simulate the filling pattern in lost foam casting and validated by comparing the simulated results to the experimental measurements. A special treatment is devised to handle the unique problem of back-pressure generated due to the evaporation of polystyrene during filling in lost foam casting. Experiments are also conducted with thermocouples embedded in the pattern of lost foam casting. With the measured temperature data, filling pattern can be derived. The mathematical model is then tested on several lost foam castings, where experimental measurements are also conducted. As the simulated filling patterns are compared with the experimental measurements, good agreement is observed.

(Received July 8, 2003; Accepted August 26, 2003)

Keywords: mold filling analysis, lost foam casting, aluminum alloys

1. Introduction

The lost foam casting (LFC) process, which is also called evaporative pattern casting (EPC) process, was invented and patented in 1958. In the process, a foam pattern is first produced, coated with a water-based refractory slurry, dried and contained in a flask filled with loose sand that is compacted through vibration. Molten metal is then poured into the mold. The foam pattern degrades immediately after molten metal is introduced, leaving a casting that duplicates all features of the foam pattern.

The LFC process offers several advantages over conventional casting processes, such as dimensional accuracy of the casting, less restrictive geometrical design requirements, no cores requirements, readily automated production and binder system emissions. Despite the advantages, castings by LFC process are more susceptible to defects, such as porosity and cold shot. This is believed to be closely related to the phenomena during filling.

Fluid flow in the LFC process, because of the existence of the pattern in the mold, is quite different from and more complex than that of the conventional casting process. For regular gravity casting, filling of molten metal proceeds with little resistance in the mold because it is initially empty. But for LFC process, the cellular structure of the foam pattern collapses, liquidizes, and then generates gases products when molten metal is poured into the cavity. Molten metal is then poured into the mold. The foam pattern degrades immediately after molten metal is introduced, leaving a casting that duplicates all features of the foam pattern.

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A variety of processing factors may affect the ease and pattern of metal filling, like the pouring temperature, material of polystyrene foam, coating conditions, design of gating/running system, design of risering system and tightness of sand mold. It is then obvious that there are complicated physical phenomena involved in the process. Based on the results of experimental research, three filling mechanisms are proposed. At low pouring temperatures (such as zinc alloy), wetting and wicking are particularly important for filling behavior. For high temperatures (such as aluminum alloy and cast iron) and low coating permeabilities, the back-pressure exerted at the metal is important. For high temperatures and high coating permeabilities, filling is controlled by the degradation of the foam. The foam pattern material used in this study is evaporative polystyrene and the poured cast metal is aluminum alloy. It is belong to the cases of back-pressure control. In the cases, a large gap between the undegraded foam and the advancing front of the molten metal is associated with this mechanism.

However, fundamental understanding of these phenomena in the process is still rather insufficient. It usually requires extensive trial-and-error procedures to determine the proper casting conditions to successfully produce a sound casting by LFC process. The initial expense and time for trying out the casting conditions are very costly. It is then very desirable for the engineer to utilize the tool of computer simulation to reduce the time and expense of selecting the right process design for LFC process.

Early study on modeling of LFC process was rare. Most efforts were made to investigate the interactions between foam patterns and molten metal or the relationships between filling behaviors and other process parameters. Efforts on modeling this complex process have been made in recent years. Wang et al. simulated the mold filling phenomena by restricting the flow front velocity via an empirical formulae based on the recession rate of foam pattern for an aluminum alloy casting. Gurdogan et al. made similar study but for ductile iron LFC castings. Chen developed a mathematical model that incorporates a partial cell method with the SOLA-VOF technique to model the filling phenomena for thin plate castings of aluminum alloy.
The purpose of this study is to develop a mathematical model to simulate the filling pattern in lost foam casting of aluminum alloy with silica-based refractory coating outside the foam and validate the mathematical model by comparing the simulated results with the experimental measurements. The research can be divided into three parts. First, a back-pressure force is proposed to account for the back-pressure effect in mold filling process and the value of the back-pressure force is unique to the particular lost foam conditions of concern. Secondly, a stepwise casting is used to obtain the appropriate value of back-pressure force based on a trial-and-error procedure of comparisons with the experimental measurements. And finally, the developed mathematical model incorporated with the back-pressure force is validated by comparing the simulated results of two parallel plate castings with the experimental measurements.

2. Mathematical Model

2.1 Algorithm for mold filling simulation

Flow of molten metal during mold filling is highly transient; the amount and location of the melt change. Calculation of the location of molten metal must be an integral part of the computational techniques used to model it. Therefore, the ways to keep track of the free surface location and define the boundary conditions become the key points to solve the transient flow field during filling.

The mathematical model includes governing differential equations, free surface tracking methods and boundary conditions. The governing equations are continuity and momentum equation. The back-pressure force to treat the effects of back-pressure in the LFC process is incorporated in the momentum equation. The SOLA-MAC technique is used for free surface tracking. In the interior region, the fluid dynamics principles to be obeyed include the continuity and momentum equation. In the surface region, the continuity equation, however, does not hold in the state of zero divergence because the flow domain may be expanding or shrinking in the surface region. Instead, the free surface should satisfy the boundary conditions that stress tangential to the surface must vanish and stress normal to the surface must balance the externally applied normal stress. For wall boundary, no-slip condition is designated in this study.

2.2 Treatment of back-pressure effects during filling

As discussed in the previous section, the filling behavior of aluminum alloys with silica-based refractory coating outside the foam, as the cases considered in this study, belongs to the category of back-pressure control. The foam and molten metal reach a dynamic pressure balance, with a sizable gap in between. Here, the speed at which metal front advances is, to a great degree, dependent on relaxation of back-pressure in the gap. When back-pressure decreases from the equilibrium value, metal front advances and comes closer to the foam pattern. This leads to an increased rate of foam degradation and faster generation of gaseous degradation products, which, in turn, produces a higher back-pressure.

In this study, the combined effects of back-pressure are represented by a back-pressure force; $F_{bi}$. It is then incorporated in the momentum equation as shown below.

$$
\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = - \frac{1}{\rho_l} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right) + g_i - F_{bi}
$$

The back-pressure force is exerted upon the molten metal in opposition to the direction of the flow. In other words, molten metal is halted by a constant force in the flow direction during filling. The three components of the back-pressure force in the three axial directions can then be described as follows.

$$
F_{bi} = F_{b} \cdot U_i / \sqrt{U_i^2 + U_j^2 + U_k^2}
$$

$$
F_{bj} = F_{b} \cdot U_j / \sqrt{U_i^2 + U_j^2 + U_k^2}
$$

$$
F_{bk} = F_{b} \cdot U_k / \sqrt{U_i^2 + U_j^2 + U_k^2}
$$

where $U_i$, $U_j$, $U_k$ are the three components of the flow velocity in the three axial directions.

In this category of back-pressure control, a variety of processing factors may affect the magnitude of the back-pressure. They include pouring temperature, material of polystyrene foam, coating conditions, design of gating/running system, design of risering system and tightness of sand mold. It is then very difficult to determine the value of the back-pressure force. To obtain the appropriate value of the back-pressure force, an iterative trial-and-error procedure of comparisons with the experimental measurements is adopted in this study.

3. Experimental Method

3.1 Experimental apparatus and setup

The experimental setup is consisted of four major parts: pattern castings, temperature detecting and recording system, mechanically driven vibration table and melting system. The first part is casting patterns. The foam pattern materials used in this study is expanded polystyrene pattern with a density of 0.035 g/cm³. There are a number of casting configurations used in this study as will be described in the later section. The second part is temperature detecting and recording system. The progress of the molten metal front inside the pattern is monitored by inserting the probes into the pattern. The probes used in this study are chromel-alumel K type series thermocouples with 0.18 mm in diameter which are surrounded by ceramic tubes with 2 mm in outside diameter. And the thermocouples are then connected to a HP data acquisition system for recording the temperature histories. The third part is a mechanically driven vibration table. Sand feeding and compaction are conducted simultaneously and the molding flask is operated under frequency of 35 Hz. The unbonded silica sand of AFS grain size number of 45.6 is used in this study. The melting procedures are bottom sand feeding, pattern locating, sand feeding couple with compacting and then sprue locating. The fourth part is the melting system. All melting is conducted in a 50 kW high frequency
(3000 Hz) induction furnace. In order to control the pouring temperature, one thermocouple is located in the sprue and one other is located in the furnace. The thermocouples are connected to a digital temperature indicator and the pouring temperature can be controlled to an accuracy of ±5 °C in this study.

3.2 Experimental procedures

The experimental procedures can be described as follows with the stepwise casting as the example.

1. The polystyrene pattern for the casting cavity is first made.
2. The constructed foam pattern is coated with a layer of water-based, low-permeability silica-based refractory coating (ZIP-ORIO) by immersion method as shown in Fig. 1(a). The slurries used are Baumés of 55 and the coating can be controlled at nearly 0.2 mm in thickness.
3. Coated clusters are allowed to dry for two days at ambient temperature and then put into a drying machine with warm wind in cycles controlled at 50 °C for 4 hours.
4. The thermocouples are inserted into the polystyrene pattern at planned locations as shown in Fig. 1(b).
5. The whole pattern is then immersed into binder-free sand and compacted on a 3-D vibration table as shown in Fig. 1(c).
6. A356 Aluminum alloy is melted to a predetermined temperature and then poured into the flask. The HP data collector is switched on just before pouring and the temperature variation of each thermocouple is then recorded.
7. After the casting is completely solidified, the casting is obtained as shown in Fig. 1(d).

4. Results and Discussions

4.1 Effects of back-pressure force on mold filling patterns

As described above, the combined effects of back-pressure are integrated into a single value of back-pressure force and expressed as an additional item, Fbi, in the momentum equation. To investigate numerically the effects of back-pressure force on the filling behavior, a simple vertical rectangular plate casting with the dimensions of 10 cm × 10 cm × 1 cm is employed in this study. The gate dimensions are 1.25 cm × 1 cm and it is located at the bottom of the left wall. The gate velocity is 10 cm/s. Simulated filling patterns in this simple rectangular plate with different values assigned for the back-pressure force (0, 500, 1000, 1500, 2000 cm/s²) are shown in Fig. 2. If there is no back-pressure effect, the filling behavior is the same as that in the gravity casting. The molten metal is filling the bottom of the casting first. When it is stopped by the right side wall, it turns upward. A large vortex can be seen in the left side of the casting as shown in the figure. If there are back-pressure effects, the inertia of the entering melt seems retarded and melt is seen to flow both...
horizontally and vertically. Molten metal proceeds in the mold with curved fronts. The velocity profiles seem more even. There is no vortex formed in the casting. It can also be seen that larger back-pressure force resulting in more rounded melt front during filling.\textsuperscript{9,10}

4.2 Determination of back-pressure force for LFC filling simulations

A stepwise casting is then adopted in this study to obtain the appropriate back-pressure force for the simulations of LFC filling. The vertical down sprue of the stepwise casting is $20 \times 20 \times 100$ (mm) in dimensions. The horizontal runner is $20 \times 80 \times 10$ (mm) and the gate is $10 \times 35 \times 7$ (mm). The casting can be divided into three steps. They are with cross sections of $50 \times 100$ (mm) and varied in thickness from 30, 15 to 7 mm. The stepwise casting of desired shape, along with the gating, risering system and thermocouples setting, are fabricated as shown in Fig. 3.

Experiments are conducted first and then simulated results with various values assigned for the back-pressure force are the compared with them to obtain the appropriate value for the back-pressure force. Four thermocouples are used to detect the contact time of the melt front. The first (S\#1) thermocouple is located at the center of gate. The second thermocouple is located at the center of the first step. The third one is located at the center of the second step and the last one is located at the center of the third step. The related positions of the thermocouples are shown in Fig. 3. The experimental results can be seen in Table 1. From the results of contact time, it can be seen that the molten metal contacts S\#1 first at nearly 3.08 s and meets S\#2 at 6.04 s. It then contacts S\#3 at 10.16 second and finally contacts S\#4 at 16.2 s.

LFC filling analyses are then conducted for the stepwise casting. The detection points for the contact times are set at the same positions as those of the thermocouples used in the experiments. The back-pressure force is set from 0 ~ 2000 cm/s$^2$ and the simulated results of contact times are compared with them to obtain the appropriate value for the back-pressure force. Larger back-pressure forces resulting in longer contact times. It can also be seen from Table 2 that a back-pressure force of 1500 cm/s$^2$ seems to get the simulated results rather close to those of the experimental measurements.

For the purpose of comparison, the simulated filling patterns for the stepwise casting are shown for gravity casting, where there is no back-pressure effects, and LFC casting, where 1500 cm/s$^2$ is assigned for the back-pressure force, in Fig. 4. For gravity casting, it can be seen in Fig. 4(a) that a stream of molten metal drops on the bottom of vertical sprue and then approaches the end of the casting quickly and finally fill out the casting from bottom to top. The contact sequences of the thermocouples are S\#1, S\#4, S\#3, and finally S\#2. But for LFC filling, molten metal enters the casting slowly with a curved flow front and the filling sequences are S\#1, S\#2, S\#3 and S\#4 as shown in Fig. 4(b).

The two results are quite different and that of the LFC filling is very close to the experimental measurements.

![Fig. 3 The shape and dimensions of the stepwise casting.](image)

<table>
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<tr>
<th>Time (s)</th>
<th>S#1 (°C)</th>
<th>S#2 (°C)</th>
<th>S#3 (°C)</th>
<th>S#4 (°C)</th>
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</table>

![Table 2 The contact-time results of the simulations and experiment.](image)
4.3 Validations of the mathematical model

In order to further validate the mathematical model and the proposed treatment of the back-pressure effects for LFC filling simulation, two parallel plates castings are then conducted in this study. The two castings are parallel plates castings with two types of running systems. The casting systems can be divided into four parts: casting, vertical down sprue, runner, and gate. The vertical down sprue is 2 cm \( \times \) 2 cm in cross section and 20 cm in height. The upper runner is set at 7.5 cm and 10 cm below the top of sprue and the bottom runner is set at the end of sprue. They are 2 cm \( \times \) 2 cm in cross section and 7 cm in length. Two castings with plate shape are connected to the gates, which are then connected to the runners. The castings dimensions are 0.9 cm \( \times \) 6 cm \( \times \) 10 cm and gate dimensions are 0.9 cm \( \times \) 4 cm \( \times \) 1 cm. The shape and dimensions of these parallel plates casting clusters are shown in Table 3 and Fig. 5.

The simulations are conducted first and then the experiments. The back-pressure force is set as 1500 cm/s\(^2\). The simulated filling patterns and the experimental observations, which are derived from the measured contact times from the thermocouple readings, are shown in Fig. 6. As molten metal is poured into the mold, the melt-front is slowed down quickly due to the decomposition of the polystyrene pattern. When melt front reaches the junction of the vertical sprue and the top runner, the melt is separated into two streams. One stream starts to flow into the top runner and then fills the upper plate. The other stream falls through the vertical sprue and then fills the lower plate. For both castings, the filling of the upper runner is earlier than that of the lower runner. Molten metal is also seen to enter the upper plate earlier than that of the lower plate. However, due to the acceleration of gravity, the filling speed of the lower plate is slightly faster than that of the upper plate. And eventually the two plates are filled at approximately the same time. These patterns can be found in both experimental measurements and simulation results. The filling times and patterns for the two parallel plates castings from the experiments and the simulations are quite consistent.

5. Summary

A mathematical model that incorporates a special treatment for the back-pressure effects has been developed to simulate the filling pattern in lost foam casting process of aluminum alloy. A back-pressure force is added in the momentum equation to account for the effects of back-pressure generated by the decomposition of polystyrene during filling.

It is also recognized that the magnitude of the back-pressure force is related to the pattern practices and
processing conditions of the specific lost foam casting process. The appropriate back-pressure force for the casting practices in this study is obtained by comparing the measured contact times in a stepwise casting to the simulated results with various values assigned for the back-pressure force. It turns out to be $1500 \, \text{cm/s}^2$.

The mathematical model with the obtained back-pressure force is then tested on two parallel plates lost foam castings, where experimental measurements are also conducted. As the simulated filling patterns are compared to the experimental measurements, good agreement is observed.

REFERENCES