Numerical simulation of mold-filling capability for a thin-walled aluminum die casting

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Abstract. Mold-filling capability is an important property of casting materials. Especially in thin-walled die casting, fast cooling of the melt by contact to the die makes complete filling difficult to ensure. Simulation is an important tool enabling investigation of filling problems, even before the die is manufactured. However, the prediction of misruns is challenging. Flow and solidification have to be computed as closely coupled. The effects of surface tension, the wetting angle and reduced melt flow due to solidification must be modeled with high precision. To meet these requirements, a finite-volume method using arbitrary polyhedral control volumes is used to solve flow and solidification as closely coupled. The Volume- of-Fluid approach is used to capture the phase separation between gas, melt and solid in connection with a High-Resolution Interface-Capturing scheme to obtain sharp interfaces between phases. To model the resistance of the dendrite network to the melt flow, an additional source term in the momentum equation was implemented. The Bolt test was performed for A356 alloys at a range of different casting temperatures. Numerical prediction of incomplete filling in the bottleneck regions agreed well with experimental findings using 3D camera scanning. The simulation enables derivation of the dependence of critical wall-thickness, i.e. the thickness which is fillable, on casting temperature and metallostatic pressure. This could prove useful in predicting filling problems ahead of casting.

1. Introduction

The filling capability of the melt is an important property for the production of solid, thin-walled castings. The mold-filling capability describes the ability of a metal to fill all parts of the geometry, including thin-walled regions. Filling the edges and corners of the mold is difficult for the melt and the penetration of the casting metal is only possible to a certain degree. An established experiment for investigating mold-filling capability is the Bolt test, designed by Engler and Ellerbrok [1] in 1974 at the Foundry Institute Aachen. Two cylinders are in contact lengthwise, forming a narrowing gap in which metal penetrates from both sides. Penetration depth decreases with cylinder height because the metallostatic pressure created by the metal column decreases as cylinder height decreases.

In this work, STAR-Cast [2,3] is used to address this challenging simulation task, which was already successfully applied for predicting misruns in thin-walled aluminum sand and TiAl centrifugal investment castings [4,5]. A brief overview of the underlying methodology is given in the next section. Special attention is paid to those features which are crucial in the prediction of misruns. The third chapter presents the Bolt test experiments, while the fourth chapter contains the validation of the simulation approach achieved by comparing simulation results from the Bolt test with experimental findings. The fifth chapter derives a useful relationship between metallic pressure and critical filling width for an A356 die casting. Finally, there is a short summary.
2. Numerical approach

Simulation of the complete casting process is based on a finite-volume method using the control volumes (CVs) of an arbitrary polyhedral shape. The transport equations for mass, momentum, energy, and phases in integral form are applied to each CV, whereby the surface and volume integrals are approximated using the midpoint rule. Linear equation systems for each variable are solved using either conjugate-gradient or algebraic-multi-grid iterative solvers. The equations describing mass (1), momentum (2), energy (3) and phase conservation (4) in a volume $V$ bounded by the surface $S$ are given below (for details see [6]):

$$\frac{\partial}{\partial t} \int_V \rho dV + \oint_S \rho \vec{v} \cdot dS = 0, \quad (1)$$

$$\frac{\partial}{\partial t} \int_V \rho \vec{v} dV + \oint_S \rho \vec{v} \cdot \vec{v} \cdot dS = \oint_T dS + \oint_V (\rho \vec{f} + S_{\sigma} + S_{rot}) dV, \quad (2)$$

$$\frac{\partial}{\partial t} \int_V \rho h dV + \oint_S \rho h \vec{v} \cdot dS = \oint_q dS + \oint_V S_Q dV, \quad (3)$$

$$\frac{\partial}{\partial t} \int_V \rho C_i dV + \oint_S C_i \vec{v} \cdot dS = \oint S_{C_i} dV, \quad (4)$$

where $t$ is time, $\rho$ is density, $\vec{v}$ is the velocity vector, $T$ is the Cauchy stress tensor, $\vec{f}$ is the body force, $h$ is the thermal enthalpy, $\vec{q}$ is the heat flux vector, $C_i$ is the volume concentration of the phase $i$ and $S_{(\rho f T \phi)}$ are source terms described below.

Mass conservation (1), pressure and velocity conservation (2) are coupled via the SIMPLE-algorithm [7, 8]. The transient term is discretized based on an implicitly Euler-segregated concept. Details of discretization and the solution method are available in [6] and are not elaborated here. Temperature distribution is computed using the enthalpy approach (3). For solidification modeling, the volume fraction of solidified liquid is determined using a tabulated fraction solid ($f_s$) vs. temperature curve ($f_s(T)$). Latent heat $L$ is released in proportion to the change in fraction solid ($S_Q = L \delta f_s/\delta T$). Details of the method are presented in [8] and are not repeated here.

To calculate surface force correctly, the method used to track the motion of the free surface must provide a sharp interface. The Volume of Fluid (VOF) approach in combination with a High Resolution Interface Capturing (HRIC) scheme is used to solve the problem: the entire fluid domain is considered to be filled with an effective fluid, whose properties vary according to the distribution of volume fractions of melt $C_m$, solid $C_s$ and gas $C_g$ ($C_m + C_s + C_g = 1$). The transport of melt, solid and gas is computed by solving transport equations for their volume fractions (4) with a source term $S_{C_i}$ for the phase change from melt to solid. To achieve sharpness of interface an HRIC scheme [6, 9] is used, which typically resolves the interface within one cell.

The normal force due to surface tension is treated using the continuum surface force (CSF) model proposed by [10], which defines a volumetric source in the momentum equation that is expressed as:

$$S_{\sigma} = -\sigma \nabla \left( \frac{\nabla C_{nl}}{\left|\nabla C_{nl}\right|} \right) \nabla C_{nl}. \quad (6)$$

To enable a prediction of misruns, flow resistance in the mushy zone must be handled correctly. Assuming that the mushy zone acts like a porous media, the fluid velocity resistance in the mushy zone can be approximated as a pressure drop [11]:
\[-\frac{\partial p}{\partial x_i} = \mu \frac{\partial v}{\partial t} + \frac{C_E}{\sqrt{K}} \rho |v| \]  

where $\mu$ is viscosity, $K$ is permeability and $C_E$ the Ergun’s coefficient. Permeability can be deduced from the Kozeny-Carman equation [12] as $K = \frac{(1-f_s)^3 \lambda_2^5}{(180f_s^2)}$, where $\lambda_2$ is the secondary dendrite-arm spacing (SDAS).

3. Mold-filling capability experiment: Bolt test

Fig. 1 shows the principle behind the Bolt test [1]: two cylinders (radius R), made either as sand or metal cores and are in contact lengthwise, form a narrowing gap (length a) in which metal penetrates from both sides. The penetration depth depends on the height of the metallostatic pressure: the higher the metal column above it, the greater the penetration depth.

![Fig. 1: Bolt test for mold-filling capability measurement](image)

Mold-filling capability is estimated as follows [13]: when metallostatic pressure is equal to capillary pressure $p = \rho g H = 2\sigma/d$, the melt stops flowing. Here $\rho$ is the density of metal, $g$ the gravity, $H$ the metallostatic pressure head, $\sigma$ the surface tension and $d$ the diameter of the round edge of the casting part. The mold filling capability $F$ is the reciprocal of the diameter of the round edge $d$, $F = 1/d$. Ideally, the diameter of the round edge $d$ can be calculated from the geometrical dimensions of the Bolt tests, $(R + d/2)^2 = R^2 + \frac{1}{4}(d+a)^2$. If so, the following equation can be derived: $F = 1/d = \frac{4R-2a}{a^2}$.

Bolt tests are carried out on an MBS KMC-4 tilting permanent mold. The mold consists of two parts, a fixed part and a movable part, both coated with ceramic materials. The mold is preheated to 230°C before melt pouring. Casting trials with AlSi7Mg0.3 (A356) were conducted at various casting temperatures: 720°C, 710°C, 700°C and 690°C in succession. The experimental procedure is as follows: 1.4 kg of overheated melt is taken from the deep part of the melting crucible (to avoid the entrainment of oxides) and transferred into the sprue cup of the Bolt test mold. When the temperature decreases to the desired casting temperature, the tilting of the mold is triggered and the mold tilts 90° at a speed of 7.4°/s. After the melt solidifies, the casting sample is removed from the mold. The mold cools to 230°C, which is measured by two thermocouples attached to the surface of the mold. The casting continues to cool down to room temperature after removal from the mold. This process is repeated several times at casting temperatures of 720°C, 710°C, 700°C and 690°C respectively.
To obtain the data about mold-filling capability, further analysis of the casting results from the Bolt test is necessary. Each casting is cut into four specimens and coated with spray for 3D camera scanning. The software VGStudio Max2.2 is applied to the data measurements from the 3D camera scanning. Fig. 2 shows the measurement methods for the feature values. As well as measuring the casting, it is also necessary to import the original mold shape into the software. Each piece needs to be placed into its original position in the mold before measurement. The bottom surface of the mold is taken as the reference surface. The first cutting position is then 50 mm above the reference surface, and the sample is cut at every 10 mm height increase. Cutting terminates at the end of sample and on average there are 5-8 cuts made on each piece. In this way, it is possible to obtain the penetration.
contour of the melt at each cross-section. A circle can be generated based on the curvature of this round front contour and its radius can be obtained. As predicted, the majority of these front penetration contours are not perfectly circular and this method could thus provide more precise data. Furthermore, critical wall thickness is also measured through the tangential or intersection point between the front curvature of the penetration contour and the approximate circle.

From the measured position data, it was possible to estimate the metallostatic pressure head. The relationship between the metallostatic pressure head and mold-filling capability is plotted in Fig. 3 (comparison at various casting temperatures). As predicted by the theoretical consideration a linear relation can be identified between mold-filling capability and the metallostatic pressure head. The mold-filling capability increases as the metallostatic pressure head increases.

4. Simulation validation

The simulation approach described in chapter 2 was applied to the Bolt test geometry shown in Fig. 4. To improve convergence and the stability of the model, the venting system was modified to a larger size. Two regions are created: one solid region for permanent molds, and one fluid region for castings. A coarse mesh is applied to the former, while the latter one, to increase the calculation efficiency, has a finer mesh. For the same reason, only a half part is simulated by the application of a symmetry plane boundary condition. Fig. 4 shows the Bolt test model.

![Fig. 4: Bolt test model (left) and applied mesh (right)](image)

**Table 1: Parameters of AlSi7Mg0.3 used in simulation**

| Properties                | Value       | Properties                | Value       |
|---------------------------|-------------|---------------------------|-------------|
| Density                   | 2500kg/m³   | Solidus temperature       | 542°C       |
| Dynamic viscosity         | 1.1mPas     | Liquidus temperature      | 610°C       |
| Specific heat capacity    | 1200J/kgK   | Surface tension           | 0.975N/m    |
| Latent heat               | 431J/g      | Wetting angle             | 135°        |
| Heat transfer coefficient | 2400W/m²K   | Thermal conductivity      | 200W/mK     |

The pressure outlet boundary condition is applied at the two free surfaces of the venting system and sprue cup shown in Fig. 4. This tilting process is modeled as the rotational motion defined within a user-defined field function. The same tilting velocity of 7.4°/s is applied as in the Bolt test.
experiments. Since the tilting angle is 90°, the tilting time is 12.2s. The material property parameters of AlSi7Mg0.3 (A356) are taken from the STAR-Cast material database. Table 1 shows the required parameters. By combining DSC analysis and micrographic investigation, the relationship between local solidification time $t_{ls}$ and secondary dendrite arm spacing (SDAS) $\lambda_2$ could be determined and can be generalized by the equation $\lambda_2 = 5.6182 \times t_{ls}^{0.4273}$. X37CrMoV5 steel is taken as the mold material. The thermal conductivity of the mold material is 30W/mK.

At the initial conditions, the quantity and position of the melt as well as the casting temperature and mold preheated temperature can be defined as being the same as in the experiments. Specifically, 1.4 kg melt is placed in a sprue cup before tilting at various casting temperature (720°C, 710°C, 700°C and 690°C). The initial temperature of the mold is set to 230°C.

![Fig. 5](image)

**Fig. 5**: Comparison of mold filling between experiment (left) and simulation (right) for the two pouring temperatures 690°C, 700°C, 710°C and 720°C.

Fig. 5 compares the final castings with the final shape of the melt as predicted by simulation. The general shape of the simulation result agrees well with the experimental findings, although differences can be found in details. The simulation results predict a steeper inside contour and the difference in penetration depth between the upper and lower parts is larger. A more quantitative comparison is provided by Fig. 6, which compares casting temperature dependence on critical wall thickness for two sections. Again, the general behavior is well predicted, while differences can be found in details. Especially at a casting temperature of 720°C, the experiment shows an increase in critical wall thickness, while thickness continues to decrease in the simulation.
Fig. 6: Comparison of casting temperature dependence on the critical wall thickness between experiment (straight line) and simulation (dotted line).

5. Impact of local pressure and casting temperature on filling capability

Metallostatic pressure and casting temperature in the range tested have pronounced and similar impact on critical wall thickness. Fig. 7 shows the dependence of critical wall thickness on the pressure increase from the top of the melt to the analyzed region at the four casting temperatures. Greater temperature or higher pressure results in a lower critical wall thickness, i.e. the possibility of filling thinner regions. Regression enabled an analysis of the dependence of critical wall thickness on pressure increase, resulting in the exponential dependence shown in Fig. 7. The equations enable an estimation of critical wall thickness ahead of casting.
6. Summary

The Bolt test was used to investigate the mold-filling capability of the aluminum alloy A356 and to validate misrun prediction capability when using the numerical approach in STAR-Cast for thin-walled aluminum die castings. In general, good agreement between experimental findings and simulation prediction could be found. The shape of the casting and the critical wall thickness agreed well, although differences in details still require further clarification. A dependence of critical wall thickness on metallostatic pressure could be deduced from the simulation result, which may be of use in designing castings.

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