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Short shots and industrial case studies: Understanding fluid flow and solidification in high pressure die casting

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ABSTRACT

The geometric complexity and high fluid speeds involved in high pressure die casting (HPDC) combine to give strongly three dimensional fluid flow with significant free surface fragmentation and splashing. A simulation method that has proved particularly suited to modelling HPDC is Smoothed Particle Hydrodynamics (SPH). Materials are approximated by particles that are free to move around rather than by fixed grids, enabling more accurate prediction of fluid flows involving complex free surface motion. Three practical industrial case studies of SPH simulated HPDC flows are presented; aluminium casting of a differential cover (automotive), an electronic housing and zinc casting of a door lock plate. These show significant detail in the fragmented fluid free surfaces and allow us to understand the predisposition to create defects such as porosity in the castings. The validation of flow predictions coupled with heat transfer and solidification is an important area for such modelling. One powerful approach is to use short shots, where insufficient metal is used in the casting or the casting shot is halted part way through, to leave the die cavity only partially filled. The frozen partial castings capture significant detail about the order of fill and the flow structures occurring during different stages of filling. Validation can occur by matching experimental and simulated short shots. Here we explore the effect of die temperature, metal super-heat and volume fill on the short shots for the casting of a simple coaster. The bulk features of the final solid castings are found to be in good agreement with the predictions, but the fine details appear to depend on surface behaviour of the solidifying metals. This potentially has significant implications for modelling HPDC.

1. Introduction

HPDC is an important process in the manufacturing of high volume and low cost components for the automotive, household products and electronics industries. Liquid metal (generally aluminium, magnesium or zinc) is injected into the die at high speed (30–100 m/s) and under high pressure through complex gate and runner systems. The geometric complexity of the dies lead to strongly three dimensional fluid flow with significant free surface fragmentation and splashing. The order in which the various parts of the die fill and the positioning of the air vents are crucial to forming homogeneous cast components with minimal entrapped voids or porosity. This is influenced by the design of the gating system and the geometry of the die. Numerical simulation offers a powerful and cost effective way to study the effectiveness of different die designs and filling processes, ultimately leading to improvements in both product quality and process productivity, including more effective control of the die filling and die thermal performance.

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Several grid or mesh based techniques have been used to simulate HPDC and other similar casting processes. Recent examples of these can be found in Yoshimura et al. [1] who used Flow3D to optimise the design of a die casting plunger tip. Kokot and Bernbeck [2] used MagmaSoft to simulate the flow through a two cavity die to produce automotive head caps. Kong et al. [3] used Fluent to simulate the flow and heat transfer in the high pressure die casting of a representative component. Among these recent examples only Kokot and Bernbeck [2] simulate HPDC geometries with any reasonable complexity in 3D. The regular finite difference mesh of MagmaSoft however leads to stair-stepping artefacts in their flow simulation results.

A simulation technique that is proving to be very effective at modelling these HPDC flows is Smoothed Particle Hydrodynamics (SPH). See [4,5] for a review of the basic method and [6] for a review of its use in industrial applications, such as die casting. SPH is a Lagrangian (grid-free) method for modelling heat and mass flows and is well suited to simulating the complex splashing free surface flows found in HPDC. In SPH, materials are approximated by particles that are free to move around rather than by fixed grids or meshes. The particles are moving interpolation points that carry with them physical properties, such as the mass of the fluid, its temperature, enthalpy, density and any other properties that are relevant. The inter-particle forces are calculated by smoothing the information from nearby particles in a way that ensures that the resultant particle motion is consistent with the motion of a corresponding real fluid, as determined by the Navier–Stokes equations.

SPH has advantages over grid or mesh based conventional fluid modelling for die casting applications because:

- Complex free surface and material interface behaviour, including fragmentation, can be modelled easily and naturally.
- Artefacts such as stair-stepping in the fluid flow introduced due to the mesh structure is absent.
- The Lagrangian framework means that there is no non-linear term in the momentum equation, thus the method handles momentum dominated flows very well.
- Metal shrinkage can be included.
- Tracking of microstructure and composition information is easy.
- Oxide formation and gas entrapment can be predicted directly as part of the simulations.

Examples of the application of SPH to thermal-flow problems include heat conduction [7], natural convection and Rayleigh-Benard convective instability [8]. SPH has now been used for modelling high pressure die casting for some time (see [9–12]). Validation has so far been mainly performed using water analogue experiments, which have previously been reported in [10,11,13]. Good quantitative agreement between SPH simulations and water analogue experiments was also obtained for gravity die casting by Ha et al. [14].

In this paper, we examine three case studies of industrial scale HPDC using SPH to predict the filling processes and allowing us to deduce the extent and distribution of porosity due to entrapment of air in the die. We then explore the use of short shots for validating SPH flow and thermal predictions for high pressure die casting. The dependence of final short shot casting shape on a range of operating parameters is studied.

2. The SPH method for fluid flow and heat transfer

The SPH method is described in detail by Monaghan [4,5] and Cleary et al. [6]. The SPH method starts with the interpolation of any function A at any position $\mathbf{r}$ using SPH smoothing which is given by:

$$A(\mathbf{r}) = \sum_b m_b \frac{A_b}{\rho_b} W(\mathbf{r} - \mathbf{r}_b, h), \tag{1}$$

where m_b and $\mathbf{r}_b$ are the mass and density of particle b and the sum is over all particles b within a radius 2 h of $\mathbf{r}$. Here $W(\mathbf{r},h)$ is a C^2 spline based interpolation or smoothing kernel with radius 2 h that approximates the shape of a Gaussian function. The gradient of the function A is given by differentiating the interpolation Eq. (1) to give:

$$\nabla A(\mathbf{r}) = \sum_b m_b \frac{A_b}{\rho_b} \nabla W(\mathbf{r} - \mathbf{r}_b, h). \tag{2}$$

Using these interpolation formulae and suitable Taylor series expansions for second order derivatives, any parabolic partial differential equations can be converted into ordinary differential equations for the motion of the particles and the rates of change of their properties.

The divergence form of the SPH continuity equation, from [5], is chosen because the gas in the die can be neglected:

$$\frac{d\rho_a}{dt} = \sum_b m_b (\mathbf{v}_a - \mathbf{v}_b) \bullet \nabla W_{ab}, \tag{3}$$

where ρ_a is the density of particle a with velocity $\mathbf{v}_a$ and m_b is the mass of particle b. We denote the position vector from particle b to particle a by $\mathbf{r}_{ab} = \mathbf{r}_a - \mathbf{r}_b$ and let $W_{ab} = W(\mathbf{r}_{ab}, h)$ be the interpolation kernel with smoothing length h evaluated at distance $|\mathbf{r}_{ab}|$. This form of the continuity equation is Galilean invariant (since the positions and velocities appear only as