Applied Mathematical Modelling 34 (2010) 2018–2033

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

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

Paul W. Cleary [a,*], Joseph Ha [a], Mahesh Prakash [a], Thang Nguyen [b]

[a] CSIRO Mathematical and Information Sciences, Private Bag 33, Clayton South, Vic 3169, Australia
[b] CSIRO Materials Science and Engineering, Private Bag 33, Clayton South, Vic 3169, Australia

ARTICLE INFO

Article history:
Received 21 August 2008
Accepted 13 October 2009
Available online 17 October 2009

Keywords:
High pressure die casting
SPH
Solidification
Short shot
Fluid flow
Casting defects

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.

* Corresponding author. Tel.: +61 3 9545 8005; fax: +61 3 9545 8080.
E-mail address: Paul.Cleary@csiro.au (P.W. Cleary).

0307-904X/$ - see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.apm.2009.10.015

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 differences), has good numerical conservation properties and is not affected by free surfaces or density discontinuities. The use of this form of the continuity equation is very important for predicting free surface flows.

As two particles approach each other, their relative velocity is negative (as is the gradient of the kernel) so that there is a positive contribution to $d\rho_a/dt$. If this rate of change is positive then the density of particle a rises, leading to a positive pressure that pushes the particles apart again. If two particles move apart, then their densities decrease creating a negative pressure that pulls the particles back towards each other. This interplay of velocity and density/pressure ensures that the particle remains "on average" equally spaced and that the density is close to uniform, so that the fluid is close to incompressible.

The momentum equation when converted to SPH form becomes the acceleration for each particle a:

$$\frac{d\mathbf{v}_a}{dt} = \mathbf{g} - \sum_b m_b \left[\left(\frac{P_b}{\rho_b^2} + \frac{P_a}{\rho_a^2} \right) - \frac{\xi}{\rho_a \rho_b} \frac{4\mu_a \mu_b}{(\mu_a + \mu_b)} \frac{\mathbf{v}_{ab}\mathbf{r}_{ab}}{\mathbf{r}_{ab}^2 + \eta^2} \right] \nabla_a W_{ab}, \tag{4}$$

where P_a and μ_a are pressure and viscosity of particle a and $\mathbf{v}_{ab} = \mathbf{v}_a - \mathbf{v}_b$. Here ξ is the viscous scaling factor [8], η is a small parameter used to smooth out the singularity at $\mathbf{r}_{ab} = 0$ and $\mathbf{g}$ is gravity.

The SPH method used here is quasi-compressible and an equation of state is used to specify the relationship between particle density and fluid pressure. A form suitable for incompressible fluids is:

$$P = P_0 \left[\left(\frac{\rho}{\rho_0} \right)^{\gamma} - 1 \right], \tag{5}$$

where P_0 is the magnitude of the pressure and ρ_0 is the reference density. For water or molten metals $\gamma = 7$. The pressure from Eq. (5) is then used in the first summation term of the SPH momentum Eq. (4) to specify the particle motion. The pressure scale factor P_0 is given by:

$$\frac{\gamma\ P_0}{\rho_0} = 100\quad V^2 = c^2, \tag{6}$$

where V is the characteristic or maximum fluid velocity and c is the speed of sound. This means that the sound speed is ten times the characteristic speed. This ensures that the density variation is less than 1% and that the flow is close to incompressible.

To simulate confined or partially confined fluid flow, such as is typically found in industrial and geophysical fluid flows, the modelling of physical boundaries is important. Boundaries in SPH can be modelled in a range of ways, but here we use approximately evenly spaced SPH particles at which a Lennard-Jones type force (a very steep polynomial potential relating the force with the displacement into the boundary) is applied in the normal direction (see [6] for a description). In the tangential direction, the boundary particles are included in the summation for the shear stress using Eq. (4) (with the pressure gradient term set to zero) to give non-slip boundary conditions on the walls.

Heat transfer is a critical element of many die casting processes. The SPH heat equation is based on the internal energy one developed in [7], but modified to use an enthalpy formulation that is more suitable for modelling solidifying metals [8]:

$$\frac{dH_a}{dt} = \sum_b \frac{4m_b}{\rho_a \rho_b} \frac{k_a k_b}{k_a + k_b} T_{ab} \frac{\mathbf{r}_{ab} \cdot \nabla_a W_{ab}}{(\mathbf{r}_{ab}^2 + \eta^2)^2}, \tag{7}$$

where the summation on the right is the heat conduction term. The enthalpy per unit mass is defined by:

$$H = \int_0^T c_p(\theta) d\theta + L[1 - f_s(T)], \tag{8}$$

where c_p is the temperature dependent specific heat, L is the latent heat and $f_s(T)$ is the volume fraction of material that is solid at temperature T, k_b is the conductivity, and $T_{ab} = T_a - T_b$. Eq. (7) has an explicit conductivity which can be temperature dependent and ensures that heat flux is automatically continuous across material interfaces, such as between a die and a liquid metal. This allows multiple materials with substantially different conductivities to be accurately simulated. Boundary conditions that are able to be used with this heat equation include, isothermal, adiabatic and convective and radiative heat loss.

3. Predicted filling of industrial parts

Three case studies of SPH prediction of the filling of actual industrial components are presented here. The filling patterns provide information about order of fill, potential sites of porosity formation, race tracking and similar defect producing flow structures. These types of predictions can then be used as inputs for improving gate, runner and venting systems design. These predictions are made using an isothermal model because the filling is so rapid compared to the heat conduction time scale that little heat loss or solidification can be expected during filling. This was confirmed as reasonable by performing the simulations for the first two case studies with coupled thermal and solidification models enabled and observing little difference. The simpler isothermal models are therefore presented in this section.

3.1. Differential cover

The first case study involves the casting of an automatic differential cover. This component has a very complex three dimensional shape. The base plate is about 250 × 250 mm square in area. A thin-walled dome-like structure rises from the base plate and has an average section thickness of about 6.5 mm. Two cylindrical bosses blend into the dome and several bolt plates are raised from the surface to allow structural attachment to the car. Liquid aluminium is injected into the die cavity through the curved gates attached to one side of the base plate. The gates are 1.5 mm thick and are fed from a runner system attached to the shot sleeve. The liquid metal in the shot sleeve is pressurised by a plunger that forces the metal out into the runner system, through the gate and into the part. In this simulation an SPH particle size of 0.75 mm is used. When the cavity is completely filled, the total number of particles is about 900,000. The liquid aluminium viscosity used was 0.01 Pa s and the density was 2700 kg/m^3.

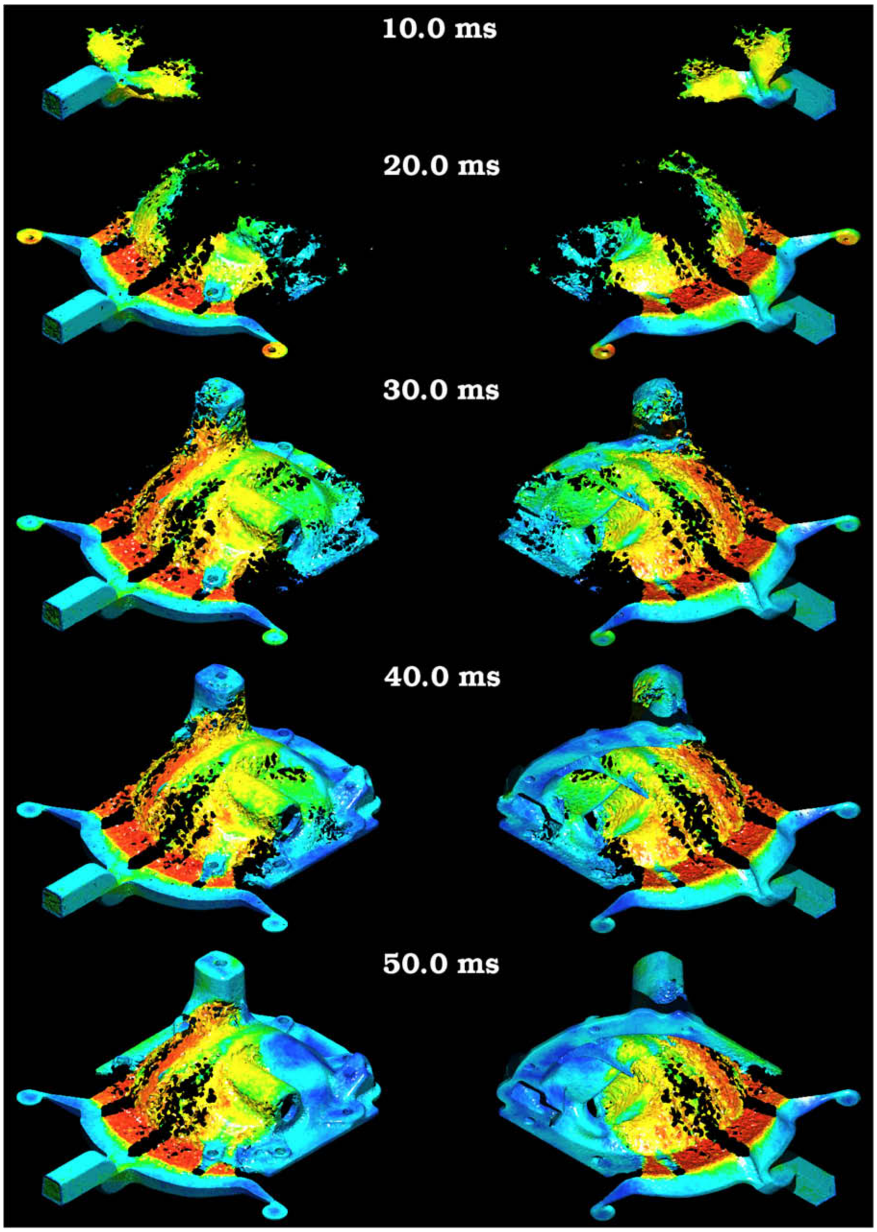

Fig. 1. Filling of differential cover with the molten metal coloured by speed with blue being slow and red being fast. The casting is shown in top view on the left and bottom view on the right. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 1 shows the filling pattern for the automotive differential cover with aluminium entering the die cavity through the four gates attached to a conventional tangential runner system with shock absorbers. At 10 ms, the initial flow of metal through the inside two gates occurs. It forms two broad jets entering the die at 45° angles (directed outwards). The structural support in the die between the central two gates ensures that a large cavity forms behind this. The outward direction of the fluid streams results from the pressure distribution in the tangential runner fed from the central runner coming from the shot sleeve. A little later fluid starts to enter the die cavity through the outer two gates creating four different streams of fluid.

After entry into the die cavity, the liquid metal partially fragments and sprays across the cavity. In regions of die curvature, the wall drag causes the fluid to slow somewhat and following fluid catches up leading to the formation of moderately coherent streams but with very fragmented boundary regions. This type of partially fragmenting partly coherent flow is a characteristic of most high pressure die casting processes [11]. It has many disadvantages in that it tends to facilitate the trapping of significant volumes of air when these streams converge and provides significant opportunity for oxide formation due to the large metal surface area exposed to air.

On one side of the die, two of the streams quickly merge leaving three main streams moving directly away from the gate following the contours of the part. These create long lasting voids in between. At 20 ms, some leading fragments of liquid begin to collect in the right flange. By 30 ms, the fluid streams merge around the middle of the die with the leading material having reached the far side of the die opposite the runner. From here it spreads sideways and progressively fills the sides and flows backwards towards the gate. This back filling process is again a characteristic of most high pressure die casting processes. It means that much of the filling occurs with fluid moving back towards the gate, which for many operators is counter-intuitive. Significant volumes of fragmented fluid are now seen to collect in the vertical boss. Sufficient amounts of the die are now filled that the shape of the casting starts to become clear.

By 40 ms, almost the entire half of the die on the far side of the gate is filled and the detailed topographic structures have become clear. There is a strong back flow along the sides and the base plate back towards the gates. The dominant void regions are now just the areas on either side of the incoming streams from the gate, some residual voids on the top behind the horizontal boss and on the sides of the vertical boss. By this stage all the exit vents that are normally attached to the base plate are blocked and all the remaining air in the die is trapped. Under high pressure this air dissolves in the liquid metal but will later come out of solution as the contraction of the solidifying metal reduces the pressure in the casting and contributes to the formation of fine gas porosity. This porosity is typically acceptable if it is not inter-linked to create "leakers" that prevent the component from being pressure tight. This porosity can limit the use of such components in applications where significant heat treatment is needed or where significant structural strength is required, although progress in improving the performance of HPDC has been achieved in recent years.

By 50 ms, there has been significant back filling and the rear third of the die is completely filled. The transition region between the fast flowing streams moving away from the gate and the back filling fluid occurs where the fluid colour (representing speed) abruptly changes from yellow to blue. The fluid in the blue slow-moving region has a low void fraction. The vertical boss is substantially filled as is the base plate on the opposite side. The last remaining areas to be filled are the central void region between the inner gates, the void created between the left most gate and the inner gate (when viewed from above), the base plate on the far left adjacent to the gate and parts of the base of the vertical boss. This suggested that the porosity will be asymmetric with a heavy weighting to the left of the casting.

3.2. Electronic housing

The second case study involved the prediction of the filling of an electronic housing. It is about 66×83 mm in area and has a section thickness of about 3 mm. Molten aluminium is injected into the die cavity through two long orthogonal side gates of height 1.3 mm branching from a central runner that is oriented at 45° to the runners and gates. The particle size used in this simulation was 0.64 mm. The liquid aluminium viscosity used was 0.01 Pa s and the density was 2700 kg/m^3.

The filling of the electronic housing is shown in Fig. 2. Fluid enters the die cavity through two gates attached to the asymmetric Y-shaped runner. The dominant flow is through the gate attached to the straighter arm of the runner on the far side of the die (as shown from the view in Fig. 2). Due to lower flow resistance the metal preferentially fills the vertical side walls around the rim of the housing above the gates. At 8.2 ms, the rim of the casting near each of the gates is filled with very fragmented metal with the leading edges of the fluid having passed the corners and starting to fill the other two sides of the die. A large fragmented stream sprays down from the side with the straighter runner into the main body of the housing shell at around a 30-degree angle.

By 13.6 ms, the leading fluid moving in each direction around the top rim of the casting have met at the opposite corner of the die cavity and have started to back fill along the sides. The 30-degree stream across the side and base of the cavity are broader and more fragmented than earlier but still clearly defined. There is a very large void to one side covering large sections of the bottom surface of the die and the two adjacent side walls. There is also a smaller but still significant void region on the other side trapped between the angled stream and the filled region above in the rim. None of the air in these parts of the die is able to reach the vents to be discharged.

By 19 ms, the back flow has substantially filled the die. Again the transition from yellow to blue shows where the incoming fluid decelerates as it encounters the more slowly moving front of back filling fluid. Some flow through the discharge vents on the right side of the die occurs at this time. The discharge of metal through the vents occurs late in the filling be-

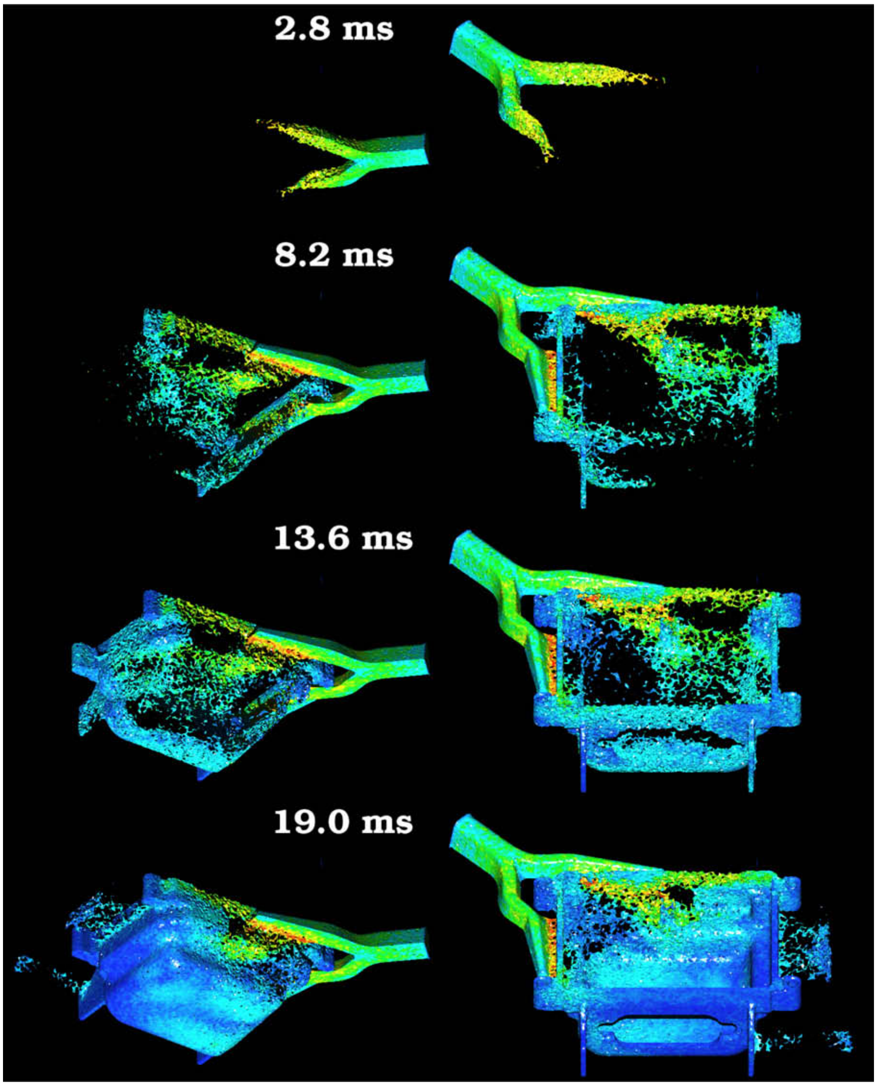

Fig. 2. An electronic housing filled from a Y-shaped runner (coloured by speed).

cause the vents are very narrow and comparable to the gate thickness. Significant back pressure is required to force fluid into the vents. At this time the back flow has started to fill the large voids on either side of the 30-degree stream. These large and long lived voids are the last regions of the die to fill and are expected to have significant porosity due to the large volume of air that would be trapped in the die when the vents are covered.

3.3. Door lock plates

The final industrial case study is the filling of the front and back plates of a door lock. Each plate is about 180 × 32 mm in area. They have similar overall shape, but small features such as the openings and screw sockets are quite different. The door lock plates are typically cast with zinc. Zinc casting is typically performed at much higher speeds and through much thinner gates than used for aluminium or magnesium.

Zinc is injected to the die cavity through a tangential runner and two long tangential gates at very high speeds of 90 m/s. The liquid zinc viscosity was 0.07 Pa s and the density was 7000 kg/m^3. The particle size used is 0.2 mm because of the very thin gates (around 0.2 mm thick) that were used for this zinc casting. When filled, the total number of particles required for this simulation is more than 2 million. So although many zinc castings are relatively small, they can be among very large high pressure die casting simulations using SPH.

Fig. 3 shows the filling pattern of the door lock plate. Initially, fluid enters the plate centrally (see frames at 1 and 2 ms). This is despite the presence of a central diamond-shaped insert which is intended to prevent this type of flow and ensure that

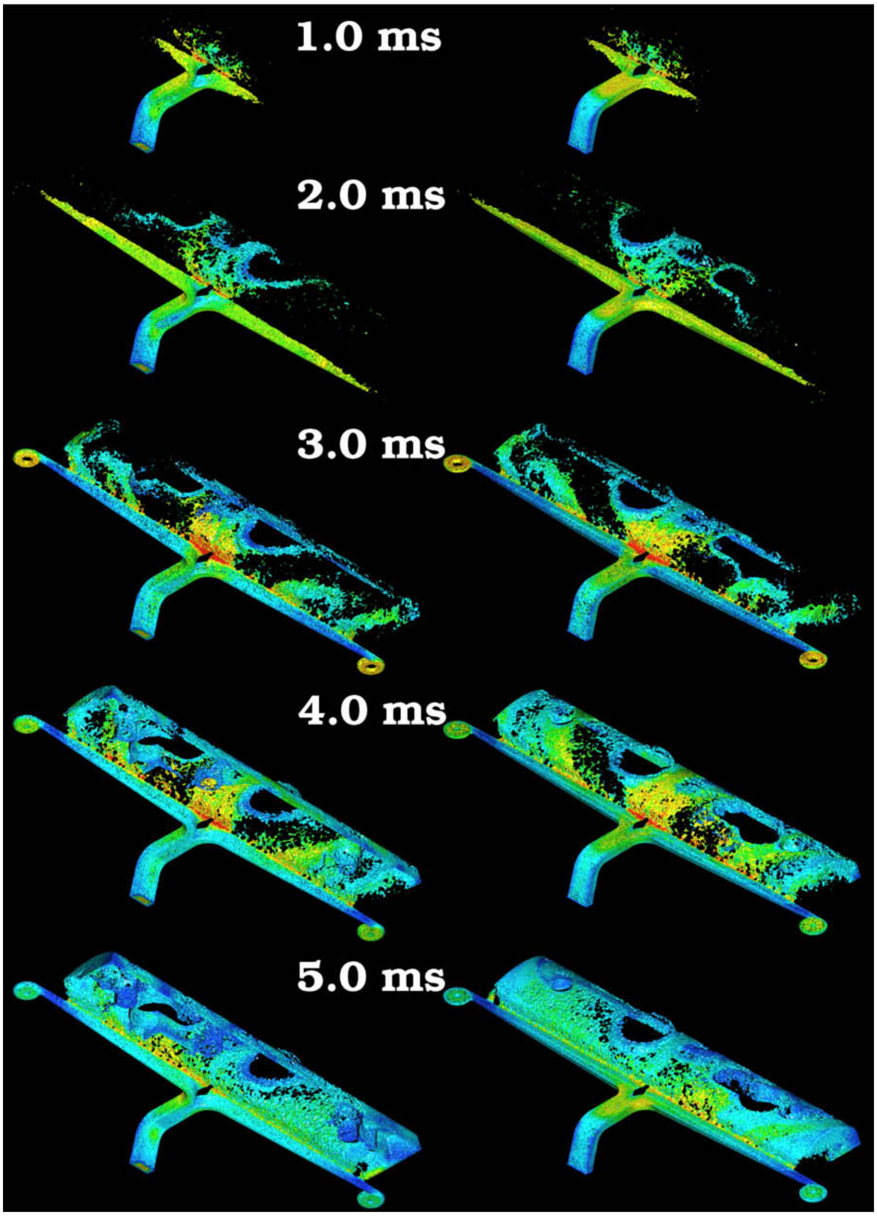

Fig. 3. Filling of the front and back plates of a zinc door lock (coloured by speed).

the metal flow spreads out equally along the tangential runners. At 2 ms, the leading fragmented fluid has started to collect around the rims of the various openings in the middle of the plates. The differences between the front and back plates now start to become clear. The initial fluid to enter the die cavity is very fragmented and due to its much longer residence time will cool substantially and start to solidify well before the adjacent regions are filled. These types of structures can be visible in final components and can affect surface finish, which is the principal concern for domestic fittings where cosmetic appearance is important.

It is only once the runner system is almost filled (3 ms) that fluid pressure rises high enough to force significant fluid to enter the plate through the very narrow gate in positions away from the centre of the runners. It does so, as four separate jets oriented roughly at 30° to the edge of the plates. At this time fluid from the central jet has reached the far sides of the plates and has rapidly race tracked along much of their opposite rims.

By 4 ms, more than 60% of the die cavities are filled. The opposite sides of the plates are filled and fluid is flowing around the rims toward the tops and bottoms of the plates and back towards the gate. The openings for the lock and handles are now clearly defined and the difference in the void distribution produced by these openings is pronounced. The boundaries of the filled regions contain significantly fragmented metal. Large voids are trapped between the filled rims, the 30-degree inclined streams and the fluid surrounding the central obstacles. Again this gas is trapped and cannot reach the vents because of the preferential filling around the rim and again this gas will manifest as fine scale porosity in the casting in these regions.

By 5 ms, the main cavities are substantially filled with some porosity observable near the gates and on the top surface of the plates just above the door handle opening. Of more importance are the very visible holes in the top and bottom edges of both plates adjacent to the gate. The flow around the rim of the plates has not been fast enough to fill these regions and the runners are too narrow near their ends to allow filling from there. These rim holes are hard to fill and could lead to either cold shuts or to surface defects from weld lines if the fairly cold leading metal was able to reach the runners and fill in these gaps.

4. Understanding short shots

Short shots are obtained by only partially filling a die cavity, generally by using a smaller shot volume or sometimes by stopping the driving piston part way through. The latter method is not normally recommended and usually results in uncontrolled casting parameters. As the metal flows, it cools and starts to solidify. Eventually the metal stops moving and freezes in place, preserving significant information about the distribution of metal in the die and the nature of the flow.

The general philosophy behind using short shorts for validation is to perform matching simulations (with fluid flow fully coupled to solidification and thermal models) and then to compare the final frozen parts. The degree of similarity or mismatch is then very revealing about both the modelling and the short shot experiment. This is not a straight-forward process since there are commonly many unknowns in the physical experiments as well as difficulties in performing the simulations. These include:

- Liquid metal temperature when approaching the gate is not well known since it is dependent on thermal losses in the shot sleeve and runner system.
- Die temperature is hard to control and may not be well known (since the die commonly will not have the opportunity to be heated over many successive shots). In the experiments reported here, the shot frequency was low and the die was essentially allowed to cool to the vicinity of room temperature between shots. This is not representative of operating conditions in a commercial die casting operation. For validation of the flow predictions and comparison with the short shots it is sufficient for them both to be at the same initial die temperature (as is done here).
- Viscosity–temperature data for the solidification models is not necessarily reliable at the level of accuracy needed for such a sensitive test.
- The relatively low spatial resolution that can be afforded in the transverse direction (orthogonal to the fluid flow in the thin sections) can affect the accuracy of thermal solution and therefore the solidification and the later flow.
- Surface effects occurring as the liquid metal slows and solidifies such as surface tension, oxide formation, and the formation of solid films with mechanical strength that need to rupture are all poorly understood and hard to represent in the numerical models.

The casting that we have chosen for these short shot experiments is a simple thin-walled coaster. A pair of tangential runners was used for the die. The matching SPH simulations use fully coupled thermal and flow solutions including heat conduction into the solid die and solidification of the liquid metal. The experimental short shot conditions were difficult to measure so we do not know accurately the initial conditions that should be used in the simulations. This uncertainty is managed by examining sensitivity of short shot prediction to variations in the uncertain input data within plausible ranges of values.

4.1. Material properties for the coupled thermal-flow model

The properties of the liquid aluminium and the die steel used in casting these short shots are given in Table 1. The solidus and liquidus temperatures for the aluminium are 536.1 and 589.7 °C respectively. The viscosity of the liquid metal varies strongly with the solidification state and therefore with its temperature and is shown in Fig. 4a. The specific heat of the aluminium is also temperature dependent and there is latent heat release as the metal solidifies. Fig. 4b shows the variation of enthalpy per unit mass with temperature. The gradient of the linear parts at the lower and higher temperatures are given by the specific heat which varies between 0.891 and 1.144 kJ/kg/K. The increase the enthalpy around 550 °C results from the latent heat whose contribution depends on the fraction of the metal that is liquid at each temperature.

Table 1
Material properties used in the coupled thermal-flow model for the short shots.

Metal	Liquid aluminium	Die steel
Density (kg/m^3)	2540.0	7644.0
Specific heat (kJ/kg/K)	1086.0	768.7
Conductivity (W/mK)	237.0	30.0

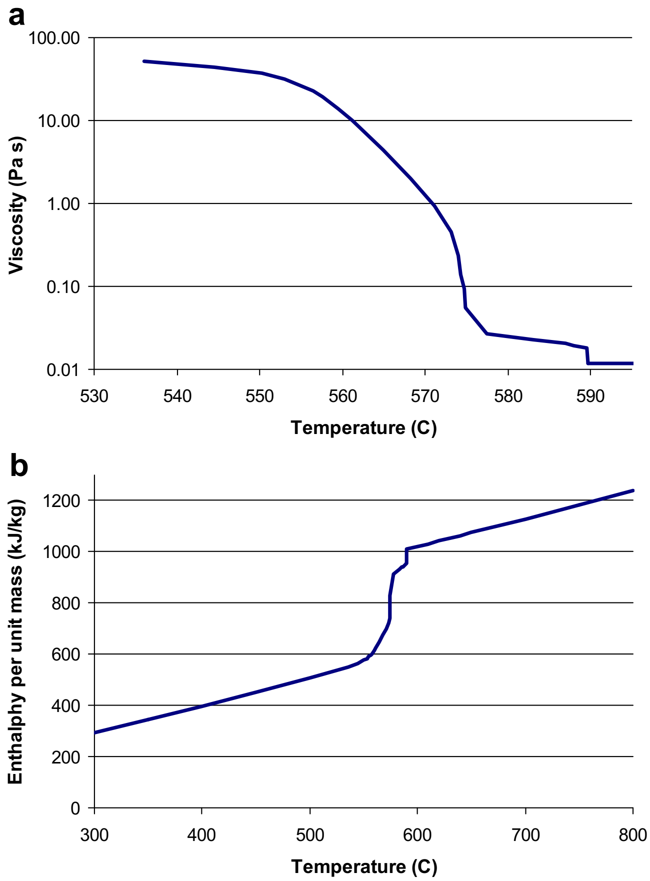

Fig. 4. Variation of liquid aluminium properties with temperature; (a) viscosity and (b) enthalpy per unit mass.

4.2. Complete filling of the coaster with solidifying metal

To begin, we show the process of fully filling this coaster die during a complete shot. Fig. 5 shows the progress of liquid metal filling the die with the colour showing the metal temperature. All the fluid is shown on the right half of the die, so the colour indicates the surface properties. On the left half the liquid is sectioned with only the material in the bottom half of the die shown.

Once the tangential runner fills and pressurises, fluid is sprayed out into the die on 45° angled trajectories towards the side walls. Liquid metal builds up along the side walls slowing as it cools and becomes more viscous. Once the metal also makes contact with the colder top and bottom walls of the die, the cooling and solidification accelerate. The central parts of the die cavity are filled with a fairly sparse and highly fragmented hot liquid metal. Along the centreline of the die, splashing liquid metal from either side collide and stick to the top and bottom walls forming a fragmented line of prematurely solid metal. The build up of metal on the sides of the die leads to a back filling flow towards the gate. At 60 ms there are four distinct unfilled areas. These are a large one directly in front of the gate, one near each of the side walls towards the end of the die and one along the centreline of the die directly adjacent to the end wall. At 80 ms, the back filling flow has closed the large void region adjacent to the gate, but the increasing viscosity of the solidifying metal makes it difficult for the fluid to flow into the last two remaining large scale voids.

4.3. Different short shot volumes

The filling process during the short shots has substantial qualitative similarity to that of the complete filling, but the solidification occurs earlier leading to cessation of the flow with only a partially filled die cavity. We will therefore not show the intermediate transient stages of these castings but will concentrate on the final cast shape.

Fig. 6 shows a comparison of an experimental and simulated short shot for the cast aluminium coaster with a 25% volume fill. The initial die was T_{DIE} = 27 °C and the casting metal in the runner had a super-heat of 0 °C (namely at about 590 °C). The simulation is coloured by viscosity, with red being a highly viscous fluid (almost solid). The predicted front profile is in good

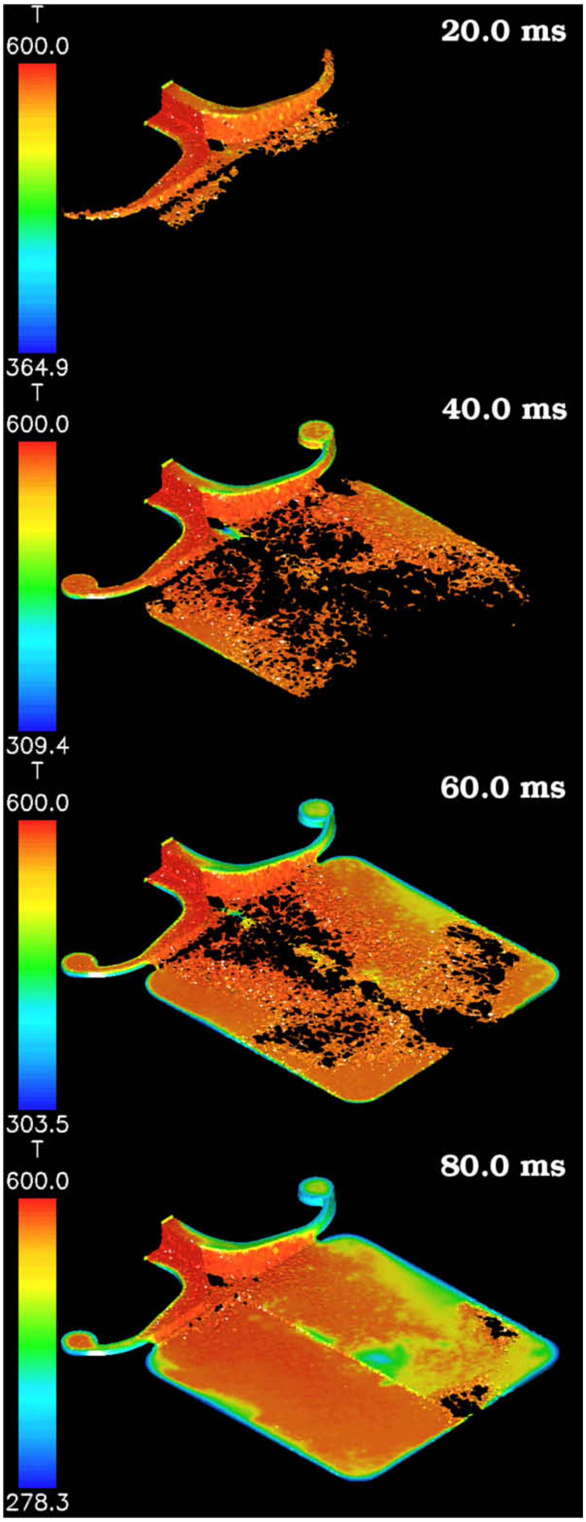

Fig. 5. Filling of coaster (including heat transfer and solidification) with fluid coloured by temperature.

agreement with the experiment. Note particularly the ability to predict the more restricted flow in the middle of the die due to the central island in the gate which acts as a significant thermal sink, leading to much more rapid solidification and less movement of the fluid front here. There is also a central small fissure in the die that seems to be predicted quite well by the simulation.

Fig. 6. Short shot with 25% volume fill: simulation (top) with colour representing viscosity, blue being low and red high; and experiment (bottom). For T_{DIE} = 27 °C and liquid metal super-heat T_{AL} = 0 °C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

There are two clear areas of difference:

1. The simulations predict a cloud of finer fragments in advance of the main front of the metal. Such leading sprays of fragments are sometimes found in HPDC short shot casting. It is not clear what controls this. A further complication is that any fragments in the experiment which are not connected to the main casting will be lost when removing the short shot. In the current case the short shot leading surface is clearly quite smooth and is rounded (when looking at its cross-section between the front and back walls). This suggests that there is some form of quite strong surface force leading to this rounded and smooth surface. In the simulation, which has no surface physics included, there are sharp and thin fragments protruding from the surface. The inclusion of any such surface force is clearly important to being able to reproduce this aspect of the casting. In traditional grid based modelling, the solutions are typically quite diffusive and small features like this are not able to be modelled.

2. In the experiment there is a long thin, asymmetric protrusion arising from a strong preferential flow along the right wall of the die. Since the entire setup is symmetric, there is no obvious cause for this strong asymmetry or for the length of this protrusion which suggests a very high speed ejection from the gate region. This phenomenon will be discussed more later.

Fig. 7 shows the short shot comparison for a 10% volume fill of the die. The simulation result is consistent with the ones seen earlier. The flow is symmetric and consists of fluid jetting at 45° angles into the die cavity. Leading fragments, some connected to the main metal surface, are again observed. The experimental short shot is quite different. There are actually three metal protuberances into the die. The one on the left is the full width of the left gate but appears to be directed straight into the cavity. This indicates that the divergence of flow created by the gate and runner arrangement is somehow dissipated. On the right, there are two metal protrusions. The more central one is erratically shaped and is the largest. The one on the right is small and shows metal barely able to penetrate into the die. In between these two metal protrusions is a region of gate from which no metal has flowed. This indicates that there is significant resistance to metal flow in some parts of the gate and higher pressures and higher flow in other parts of the gate. At the early stage where these protrusions are created, the metal is only slightly solidified and, in principle, should be free flowing, leading to the flow pattern observed in the experiment.

This very low volume short shot is the most variable of the cases we tested and has the highest degree of divergence. The simulation and short shot comparison is improved at 25% (Fig. 6) and continues to improve at 33%. This suggests that whatever physics is occurring here is mainly affecting the very early entry of metal in the die cavity. As the die filling increases, this effect fades progressively in importance. It is also clear that whatever physics is occurring is not being captured by the SPH method or indeed by any other current simulation methods.

Our hypothesis is as follows:

1. As the runner fills, free flowing liquid metal is restrained from passing through the gate by the surface tension of the metal interface at the narrow opening.
2. As the runner fills progressively, a solid skin forms on the restrained metal free surface along the gate. This skin has mechanical strength and holds back the fluid at the gate.
3. Once the runner is sufficiently pressurised, the force on the restraining solid skin increases and it ruptures.
4. High speed fluid erupts from the holes torn in the skin.

This phenomenon would explain why the early flow in the 10% short shot was so different at different locations along the gate. As the pressure in the runner rises, the precise locations where it will burst will depend on some subtle and random factors, such as location of impurities in the surface film and exact thickness of the film along its length. Each rupture will lead to hot metal squirting into the die from that location. So every different rupture pattern will produce

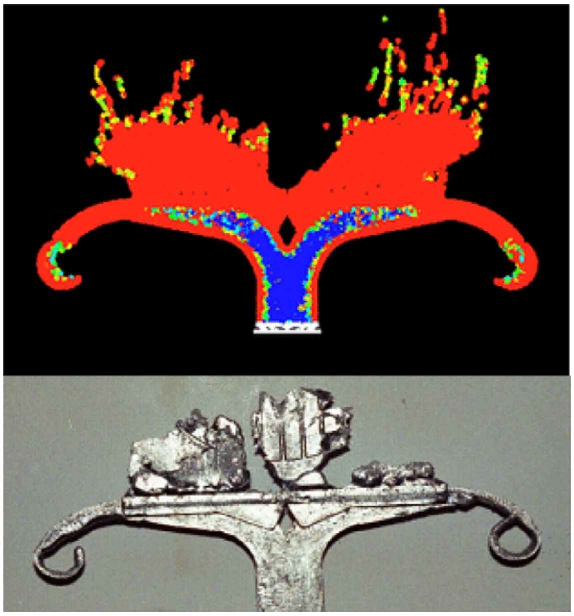

Fig. 7. Short shot with 10% volume fill: simulation (top) and experiment (bottom). For $T_{DIE} = 27$ °C and liquid metal super-heat $T_{AL} = -10$ °C.

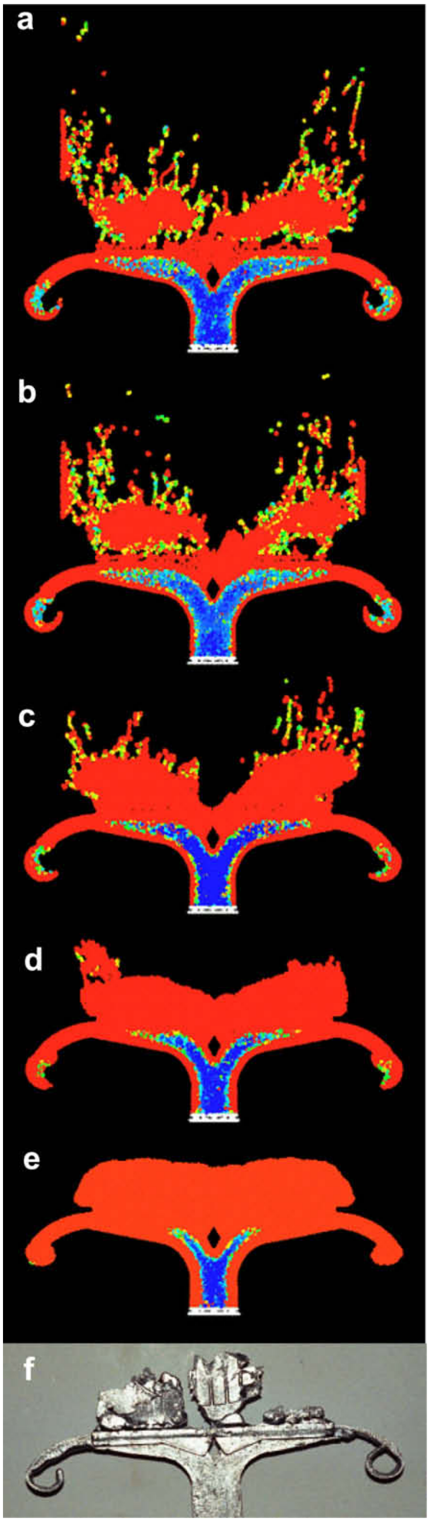

Fig. 8. Short shot variation for a 10% fill with different initial metal temperatures (degree of super-heat) (a) T_{AL} = +10 °C, (b) 0 °C, (c) −10 °C, (d) −15 °C, (e) −20 °C and (f) the actual short shot.

a different distribution of jets. This rupturing of a surface film and jetting high pressure metal into the die would very adequately explain the long asymmetric protrusion on the right of the 25% short shot. These rupturing effects will only be short lived. As soon as the excess pressure in the runner is released or the film is fully ruptured, then fluid will flow

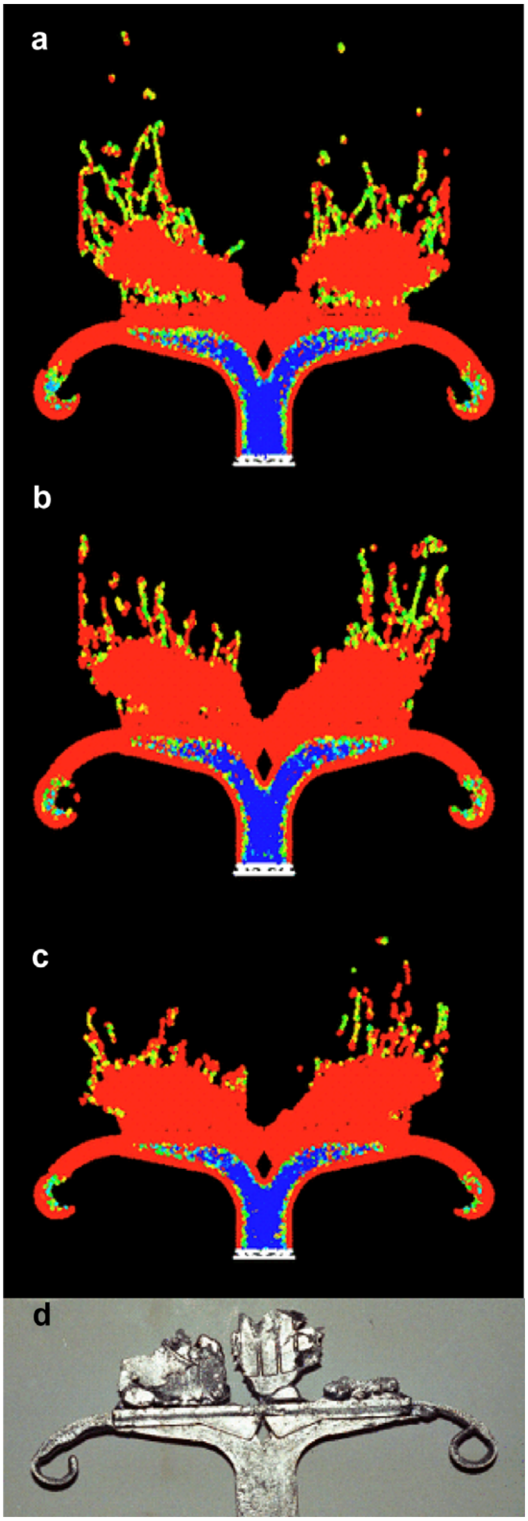

Fig. 9. Short shot variation for a 10% fill for different initial die temperatures: (a) $T_{DIE} = 127$ °C, (b) $T_{DIE} = 77$ °C, (c) $T_{DIE} = 27$ °C and (d) the experimental short shot. The degree of super-heat of the liquid metal in all cases is $T_{AL} = -10$ °C.

through all locations along the gates as intended. The later entering liquid metal will often catch up and overrun elements of the early filling leading to a progressively more symmetric filling that is progressively closer to the more idealized filling pattern predicted by the simulations.

What this would mean is that much of the detail of the early stages of the filling process, particularly near the gate will depend on the details of the bursting of the solid skin of film that forms over the gate during runner filling. The distribution of flaws in the film that will determine the rupture locations will depend on subtle variations in the temperature, composition and impurities in the incoming liquid metal. This introduces a natural variability into the die casting process that is particularly difficult to control, particularly for smaller castings. This would explain the apparent inherent high variability that is perennially observed in HPDC. It would mean that the variability is not directly related to the normally observable and controllable process variables, but would be controlled by defect distributions on the skin surface and the skin strength. These would be influenced by the process controls and the fluid flow, but there would be an inherently strong stochastic element. The only effective solutions to this problem would be to perform the casting in a vacuum or inert atmosphere or to increase the gate thickness in order to make the formation of such a mechanically strong barrier significantly more difficult. Both of these approaches would significantly increase process costs and are undesirable.

This phenomenon has significant implications for numerical modelling of HPDC as these small scale surface interface phenomena, including skins with mechanical strength, will need to be included in the models. These are inherently small scale and difficult to predict accurately. It is also extremely difficult to obtain data on surface film thickness, strength, surface tension forces or surface oxide generation making data availability for models a major challenge.

The ability of the solidifying metal to prevent the creation of fine spray and small sharp protruding features (in order to produce relatively smooth metal surfaces) also suggests either surface tension or metal and metal oxide skin formation which would impede the natural ability of the liquid to fragment. This would explain the apparent randomness of when smooth surfaces or fragmented sprays from the surfaces are observed in short shots. These phenomena represent a major challenge, not only for modelling, but to experimentalists since they are fundamentally hard to investigate and little is known about them. What does surface tension mean on a solidifying metal surface with deepening oxide layers where both the oxide layer and solidified metal skin have sufficient mechanical strength to retard the fluid?

4.4. Effect of liquid metal super-heat

It is useful to understand the effect of the metal temperature when it enters the die on the nature of the short shot. Fig. 8 shows a comparison of experimental and simulated short shot for the cast aluminium coaster with a 10% volume fill for various levels of super-heat of the incoming metal. As before, the fluid is coloured by viscosity, with red being a highly viscous fluid (almost solid).

At a super-heat of +10 °C (Fig. 8a) the metal enters the die in a free flowing state. It comes to rest in bands that are only slightly connected to the gate. There is significant spray and a moderate accumulation on the side walls. At a super-heat of 0 °C (metal is at the liquidus temperature) (Fig. 8b) the flow is quite similar with significant spray and fragmentation and the main deposits of metal being only mildly connected to the metal in the runner.

At a super-heat of −10 °C (Fig. 8c) there is significantly reduced fragmentation, but still some spray precedes the progress of the main metal fronts. The main metal deposits are now contiguous with the metal in the gate and runners. The shock absorbers are less filled than for the hotter metal cases.

At a super-heat of −15 °C (Fig. 8d) there is strong qualitative change in the metal behaviour. There is only a mild amount of jetting spray on the outer corners of the metal deposits. These are now relatively smooth with a clearly defined metal surface.

At a super-heat of −20 °C (Fig. 8e), the metal front is very smooth and there is no sign of jetting or spray from the surface. This shows that solidification can constrain the surface fragmentation, but if more than the leading edge of material solidifies there is significant change in the flow pattern which is very far from the short shot structure. The flow is clearly comparatively slow and viscous, probably more like thixoforming rather than HPDC.

Based on these comparisons, we would estimate that the most likely metal injection temperature in the short shot experiments was around 580 °C corresponding to a super-heat of −10 °C.

4.5. Effect of initial die temperature

Using the most likely liquid metal temperature we performed a series of short shot simulations for different initial die temperature. These are shown in Fig. 9 for a 10% volume fill. The fluid is again coloured by viscosity, with red being a highly viscous fluid (almost solid).

For a die temperature of 127 °C (a reasonable temperature if several shots are performed in quick succession) the fluid remains free flowing for longer since the die represents a weaker heat sink and so solidification takes longer. The final short shot looks a lot like the high super-heat cases shown earlier. There is significant spray and fragmentation from the leading free surfaces and the main metal deposits are moderately separated from the gate.

At the colder die temperature of 77 °C, the amount of spray is reasonably reduced and the main metal deposits lie closer to the gate and are connected to the metal in the runners. With a further decrease in die temperature to room temperature (27 °C) the amount of spray is sharply reduced and the metal is all deposited close to the gate. The best match with the experimental short shots is for this temperature, which is anecdotally consistent with the experimental reports that the shots occurred with significant time lapse in between. The remaining differences between the short shot and the simulation we attribute to the interfacial forces from either surface tension or the solidification and oxidation of mechanically strong surface skins.

5. Conclusion

The filling by HPDC of three industrial components, ranging from a zinc door lock to an aluminium differential cover, was simulated in 3D using SPH. Several generic aspects are common to all these flows. The gate arrangement determines how many incoming streams the fluid sub-divides into. The initial jets are fast and very fragmented. They rapidly reach the opposite sides of the die and then start filling back towards the gates. Fluid typically race tracks around the thicker structural rims of the components blocking all the discharge vents early in the filling process and leading to large volumes of trapped air. This trapped air guarantees that there will be fine scale porosity. The timing of the blocking of the vents determines the extent of the gas porosity problem. The details of later flow pattern then determine the distribution of this gas porosity in the final casting. The topography of the thin-walled castings typically manufactured with HPDC determines how the incoming fluid streams distribute fluid within the die. So overall, the HPDC flows are complex and are affected strongly by details of the geometry of the die cavity, the metal flow and venting systems. The detail obtained in the SPH filling predictions is high and the last locations to fill are indicative of where porosity can be expected due to trapping of large volumes of air within the die cavities.

As part of the validation process, experimental short shots were compared to matching SPH simulations for a simple coaster with tangential runners. These simulations used full thermal solutions coupled to the flow solution and solidification model and included heat flow within the die walls. For fill volumes of 25% and above the simulations were able to capture significant amounts of the structure of the experimental short shot shapes. For a 10% fill volume, reasonable differences were apparent. Sensitivity of the short shot shape predictions to all operating conditions was examined to understand their influence on the final shape.

The nature of the experimental short shots suggests the formation of a solid metal or metal oxide skin, with mechanical strength, across the gate during the runner filling stage. Once the runner is substantially pressurised this skin then bursts and ejects fluid into the die. The details of skin bursting process appear to control much of the early detail of the fluid flow within the die cavity. In particular, it appears to enable the creation of long thin protuberances into the die cavity arising from the high speeds following the skin bursting and can introduce significant asymmetry into the filling process. It is likely that the locations where the films burst will depend on the film thickness and the location of impurities and that these in turn will have a strongly stochastic aspect. This helps explain the apparent high variability observed in even tightly controlled HPDC, particularly for small components. This effect influences the flow most strongly early in the filling and close to the gate. As the die becomes larger or the extent of filling is larger, the importance of this effect fades. The occurrence of surface films with strengths would also help explain the apparent randomness of when smooth metal fronts are found or when fine sprays of fragments from the surfaces are observed. This presents significant challenges to experimentalists to measure and understand these types of surface processes in what are very difficult environments to measure things accurately and to modellers who would need to include these fine scale surface effects in their modelling.

References

[1] T. Yoshimura, K. Yano, T. Fukui, S. Yamamoto, S. Nishido, M. Watanabe, Y. Nemoto, Optimum design of die casting plunger tip considering air entrainment, in: Proceedings of the 10th Asian Foundry Congress, Nagoya, Japan, 2008.
[2] V. Kokot, P. Bernbeck, What is a good gating system? or Quantifying quality but how? Paper No.: 179041, in: Proceedings of the XX MCWASP Conference, France, 2006.
[3] L.X. Kong, F.H. She, W.M. Gao, S. Nahavandi, P.D. Hodgson, Integrated optimisation system for high pressure die casting processes, J. Mater. Process. Technol. 201 (2008) 629–634.
[4] J.J. Monaghan, Smoothed particle hydrodynamics, Ann. Rev. Astron. Astrophys. 30 (1992) 543–574.
[5] J.J. Monaghan, Simulating free surface flows with SPH, J. Comput. Phys. 110 (1994) 399–406.
[6] P.W. Cleary, M. Prakash, J. Ha, N. Stokes, C. Scott, Smooth particle hydrodynamics: status and future potential, Prog. Comput. Fluid Dynam. 7 (2007) 70–90.
[7] P.W. Cleary, J.J. Monaghan, Conduction modelling using smoothed particle hydrodynamics, J. Comput. Phys. 148 (1999) 227–264.
[8] P.W. Cleary, Modelling confined multi-material heat and mass flows using SPH, Appl. Math. Model. 22 (1998) 981–993.
[9] W. Thorpe, P.W. Cleary, J. Ha, N. Stokes, V. Ahuja, M. Jahedi, Simulation of fluid flow within the die cavity in high pressure die casting using smooth particle hydrodynamics, in: Proceedings of the 20th International Die Casting Congress and Exposition, 1999, pp. 23–36.
[10] P.W. Cleary, J. Ha, V. Ahuja, High pressure die casting simulation using smoothed particle hydrodynamics, Int. J. Cast Metal. Res. 12 (2000) 335–355.
[11] P.W. Cleary, J. Ha, M. Prakash, T. Nguyen, 3D SPH flow predictions and validation for high pressure die casting of automotive components, Appl. Math. Model. 30 (2006) 1406–1427.
[12] J. Ha, P.W. Cleary, Simulation of high pressure die filling of a moderately complex industrial object using Smoothed Particle Hydrodynamics, Int. J. Cast Metal. Res. 18 (2005) 81–92.
[13] J. Ha, P.W. Cleary, Comparison of SPH simulations of high pressure die casting with the experiments and VOF simulations of Schmidt and Klein, Int. J. Cast Metal. Res. 12 (2000) 409–418.
[14] J. Ha, P.W. Cleary, V. Alguine, T. Nguyen, Simulation of die filling in gravity die casting using SPH and MAGMAsoft, in: Proceedings of the Second International Conference on CFD in Minerals and Process Industries, Melbourne, Australia, 1999, pp. 423–428.