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INDUSTRIAL SCALE DIE FILLING AND THE USE OF SHORT SHOTS TO UNDERSTAND THERMAL AND FLOW EFFECTS

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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 examples 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.

The validation of flow predictions coupled with heat transfer and solidification is an important area for such modelling. One 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 partially filled. The frozen partial castings capture significant detail of the order of fill and about the flow structures occurring during 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. 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.

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 to 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. 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.

A simulation technique that is proving to be very effective at modelling these HPDC flows is Smoothed Particle Hydrodynamic (SPH). See Monaghan (1992, 1994, 2005) for a review of the basic method and Cleary et al (2005) 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 here. 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 for modelling some die casting:

- Complex free surface and material interface behaviour, including fragmentation, can be modelled easily and naturally.
- The Lagrangian framework means that there is no non-linear term in the momentum equation, thus the method handles momentum dominated flows very well.
- Ability to include shrinkage
- Ability to easily track microstructure and composition information
- Ability to predict oxide formation and gas entrapment directly as part of the simulations

Complicated physics such as multiple phases, realistic equations of state, compressibility, solidification, fracturing, porous media flow, electro-magnetics and history dependence of material properties are also easier to implement.

Examples of its applications to thermal flow problems include heat conduction (Cleary and Monaghan, 1999), natural convection and Rayleigh-Benard convective instability (Cleary, 1998). SPH has now been used for modelling high pressure die casting for some time (Thorpe et al, 1999, Cleary and Ha, 1999 and Cleary et al, 2004). Validation has so far been mainly performed using water analogue experiments, which have previously been reported in Cleary et al (2000), Ha and Cleary (2000) and Cleary et al (2004). Good quantitative agreement between SPH simulations and water analogue experiments was also obtained for gravity die casting (Ha et al., 1999).

In this paper, we provide three further examples of SPH simulation in 3D of industrial scale HPDC. We also explore more comprehensively the use of short shots for validation and this dependence of short shot shape on a range of operating parameters.

PREDICTED FILLING OF INDUSTRIAL PARTS

SPH simulations of the filling of three industrial components are presented here. The filling patterns provide information about potential sites of porosity formation. These can then be used as inputs for developing improved gate, runner and venting systems.

Differential Cover

The filling of an automotive differential cover is shown in Figure 1. The part is about 250 mm x 250 mm in area and has a section thickness of about 6.5 mm. Liquid aluminium is fed into the die cavity through the curved gates that are 1.5 mm high. The particle size used is 0.75 mm. When the cavity is completely filled, the total number of particles is about 900,000.

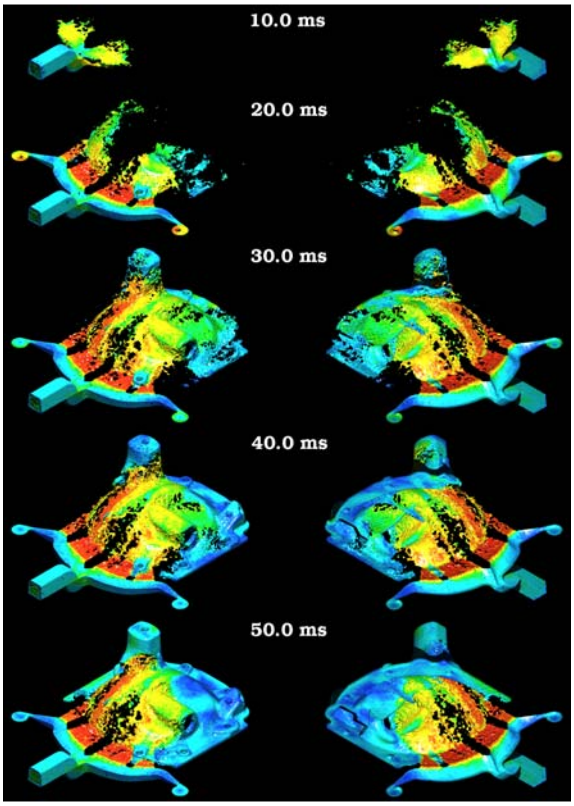

Figure 1: Filling of differential cover with the fluid coloured by speed with blue being slow and red being fast.

Figure 1 shows the filling pattern with aluminium entering the die cavity through the four gates attached to a conventional tangential runner system with shock absorbers. After entry into the die cavity, 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 circular structure on the right of the die (viewed from above). By 30 ms, the fluid streams merge around the middle of the dies 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. Significant amounts of fragmented fluid are now seen to collect in the raised “tower” on the left side of the die (viewed from above).

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 tower structure is substantially filled as is the base plate on the opposite side. The last remaining area to be filled is the central void region closest to the runner system.

Electronic Housing

Next we present the prediction of the filling of an electronic housing. It is about 66 mm x 83 mm in area and has a section thickness of about 3 mm. Liquid aluminium is fed into the die cavity through two long orthogonal side gates of height 1.3 mm feeding from a central runner. The particle size used was 0.64 mm. The filling is shown in Figure 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 Figure 2). Due to lower flow resistance the metal preferentially fills the vertical side walls around the rim of the housing above the gates.

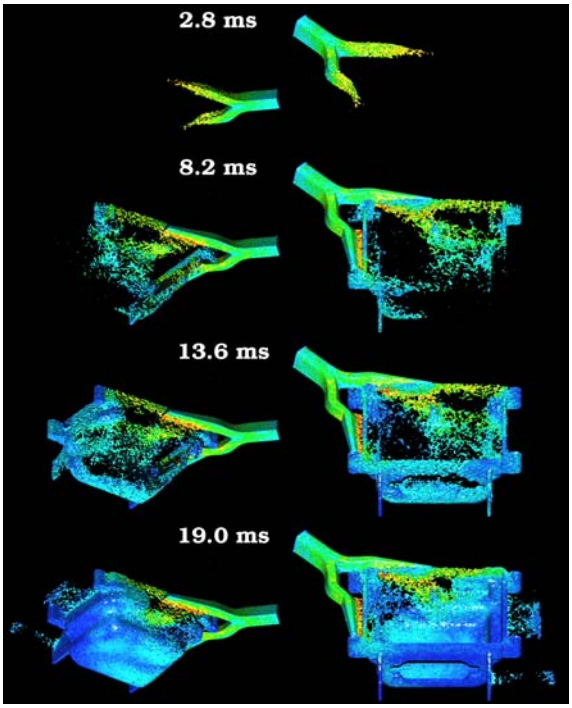

Figure 2: An electronic housing filled from a Y shaped runner (coloured by speed).

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 vents on the right side of the die occurs at this time. The discharge of metal through the vents occurs late in the filling because 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 jets. These large and long lived voids are the last regions of the die to fill and could be expected to have porosity due to the large volume of air that would be trapped in the die when the vents were covered.

Door Lock Plates

The final industrial example is the filling of the front and back plates of a door lock. Each plate is about 180 mm x 32 mm in area. They have the same overall shape, but the small structures such as the openings and screw sockets are quite different. A tangential runner system feeds liquid zinc through two long tangential gates at very high speeds of 90 m/s. The particle size used is 0.2 mm because of the very thin gates (around 0.2 mm thick) used for zinc casting. When filled, the total number of particles is more than 2 million, so although many zinc castings are relatively small, they can involve very large simulations.

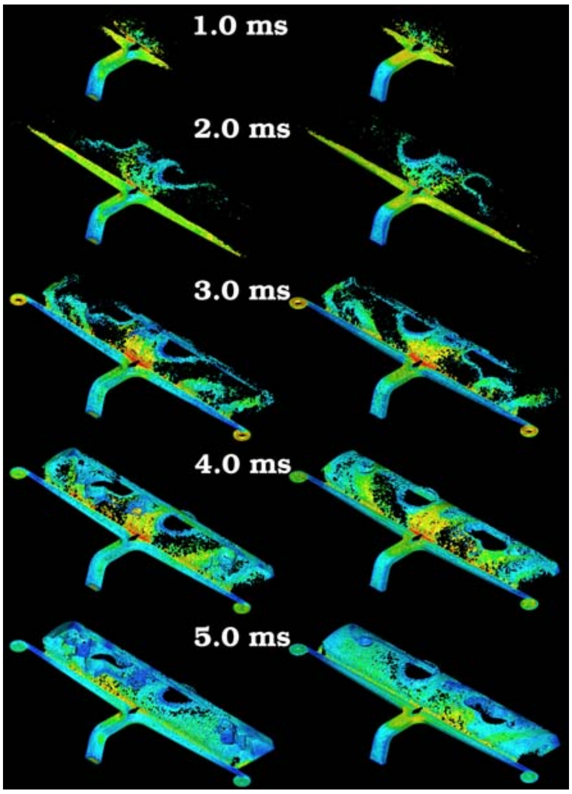

Figure 3: Filling by zinc of the front and back plates of a door lock (coloured by speed).

Figure 3 shows the filling pattern of the door lock plate. Initially, fluid enters the plate centrally (see frames at 1 and 2 ms) despite the presence of a central diamond shaped cut-out intended to prevent this and ensure that metal flowed along the tangential runners. At 2 ms, the leading fragmented fluid has started to collect around the rims of the various openings in the plates and the differences between the front and back plates starts to become clear. It is only when the runner system is almost filled (3 ms) that fluid is forced to enter the plate through the gate away from the central region. It does so as four different jets oriented roughly at 30 degrees 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 edges.

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. 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 clear 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 these gaps.

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. As the metal flows, it cools and starts to solidify. Eventually the metal stops moving and freezes in place, preserving significant amounts of 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 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 unknown or is poorly known.
- 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.
- 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 later flow.
- Surface effects as liquid metal slows and solidifies such as surface tension, oxide formation, 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. It was cast using a pair of tangential runners fed from a single shot sleeve. The matching simulations use fully coupled thermal and flow solutions using SPH including heat conduction into the solid die and solidification of the liquid metal. The experimental short shot conditions were not well characterised so we do not know accurately the initial conditions that should be used in the simulations.

Complete filling of the coaster with solidifying metal

To begin, we show the process of fully filling this coaster die during a complete shot. Figure 4 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.

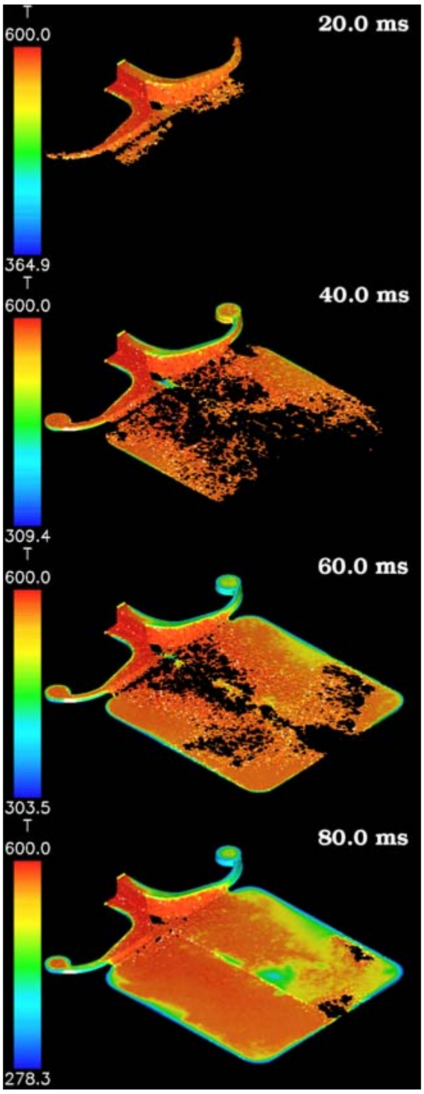

Figure 4: Filling of coaster (including heat transfer and solidification) with fluid coloured by temperature.

Once the tangential runner fills and pressurises, fluid is sprayed out into the die on 45 degree 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.

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.

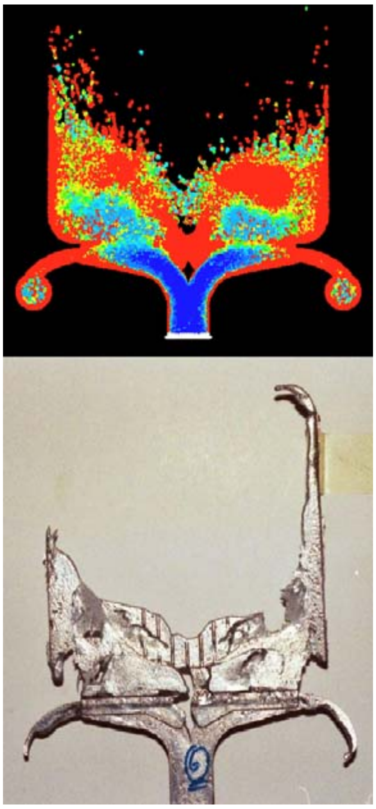

Figure 5: Short shot with 25% volume fill: (top), simulation (bottom) experiment. For T_{DIE} = 27^{o}C and metal super-heat T_{AL} = 0^{o}C.

Figure 5 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 ^{o}C and the casting metal injection temperature had a superheat of 0^{o}C (590 ^{o}C). The simulation is coloured by viscosity, with red being a highly viscous fluid (almost solid). The predicted front profile is in good 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.

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 and sometimes not. 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 force physics included, there are clearly sharp and thin fragments protruding from the surface. The absence of any surface force is clearly important in 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 nor the length of this protrusion which suggests a very high speed ejection from the gate region.

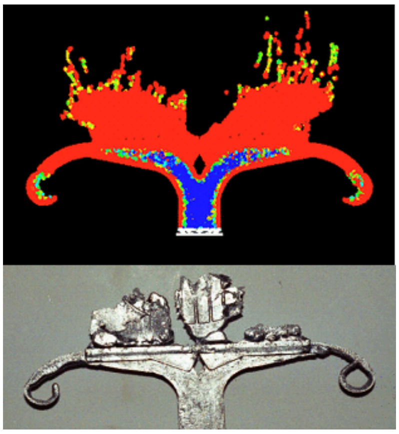

Figure 6: Short shot with 10% volume fill: (top), simulation (bottom) experiment. For T_{DIE} = 27^{o}C and metal super-heat T_{AL} = -10^{o}C.

Figure 6 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 45º 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% (Figure 5) 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. It is also clear that whatever physics is occurring is not being captured by SPH or any other current simulation model.

Our hypothesis is:

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.
3. Once the runner is sufficiently pressurized, the force on the restraining solid skin increases and it ruptures
4. High speed fluid erupts from the holes torn in the skin.

This type of process would explain why the early flow in the 10% short shot was so different at different locations along the gate. It would also explain the long asymmetric protrusion on the right of the 25% short shot.

What this would mean is that much of the detail of the filling process, particularly early on and particularly near the gate depends on the details of the bursting of the solid skin that forms over the gate during runner filling. This would explain the apparent inherent variability 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 component. 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 to make the formation of such a mechanically strong barrier significantly more difficult.

This 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.

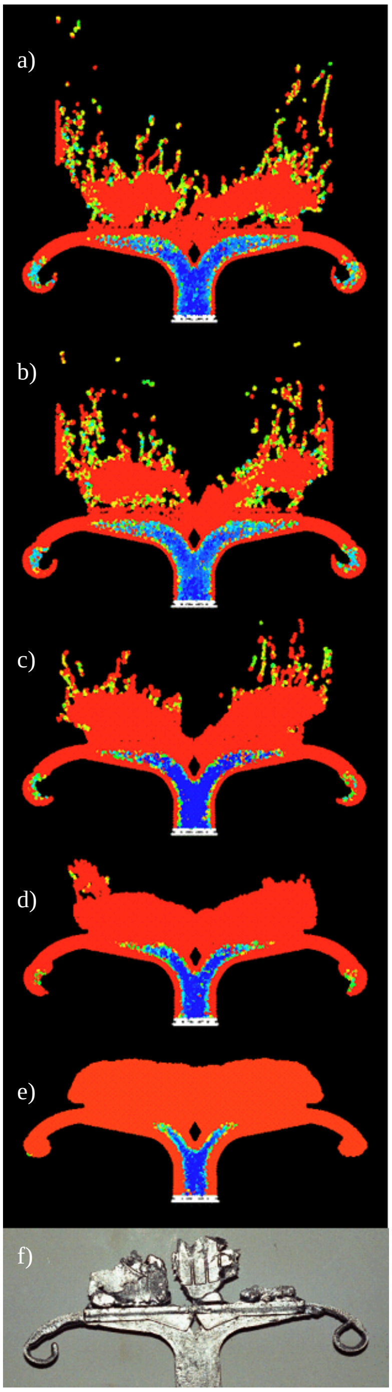

Figure 7: Short shot variation for a 10% fill with different initial metal temperatures (degree of super-heat) a) T_{AL} = +10^{o}C, b) 0^{o}C, c) -10^{o}C, d) -15^{o}C, e) -20^{o}C and f) the actual short shot.

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. 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?

Effect of 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. Figure 7 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^{o}C (Figure 7a) 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^{o}C (metal is at the liquidus temperature) (Figure 7b) 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^{o}C (Figure 7c) 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^{o}C (Figure 7d) 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^{o}C (Figure 7e), 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 ^{o}C corresponding to a super-heat of -10^{o}C.

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 Figure 8 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^{o}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.

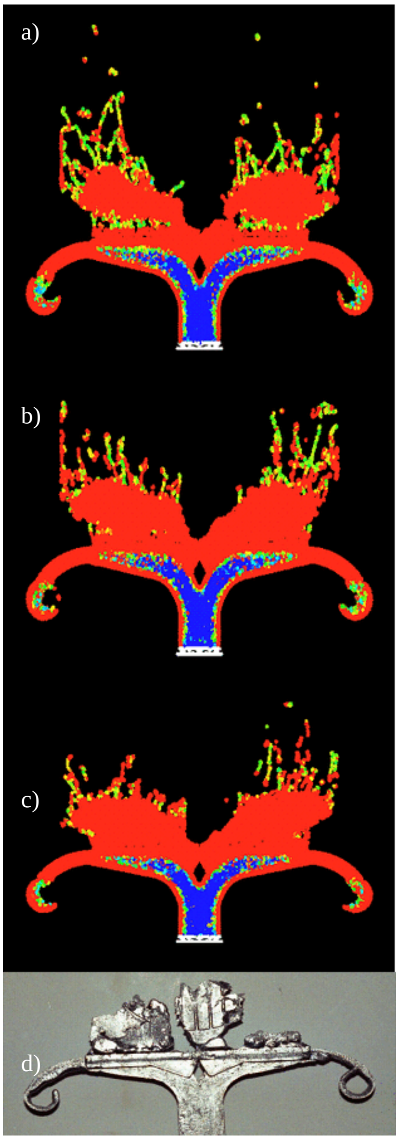

Figure 8: Short shot variation for a 10% fill for different initial die temperatures, a) 127^{o}C, b) 77^{o}C, c) 27^{o}C and d) the actual short shot. The degree of super-heat in all cases is T_{AL} = -10 C / 580 C.

At the colder die temperature of 77^{o}C, the amount of spray is reasonably reduced and the main metals 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^{o}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 surface interface forces from either surface tension or the solidification and oxidation of mechanically strong surface skins.

CONCLUSION

The filling by HPDC of three industrial components, ranging from a zinc door lock, to an aluminium differential cover were simulated in 3D using SPH. The detail in the filling predictions is high and the last locations to fill correlate well with porosity/voidage observations made by manufacturers of these components.

As part of validation, experimental short shots were compared to matching SPH simulations for a simple coaster with tangential runners. For fill volumes of 25% and above the simulations were able to capture significant amounts of the structure of the short shots. For a 10% fill volume, reasonable differences emerge. The nature of the experimental short shots suggests the formation of a solid metal or metal oxide skin, with mechanical strength, across the gate. The bursting of this skin appears to control much of the early detail of the flow structure. In particular it appears to enable the creation of long thin protruberances into the die cavity arising from the high speeds following the skin bursting. This phenomenon would explain the very high degree of variability experienced in HPDC. It presents significant challenges to experimentalists to measure and understand this phenomena and to modellers to include these surface effects in their modelling.

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