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SPH: A NEW WAY OF MODELLING 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 Lagrangian simulation technique that is particularly well 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 the accurate prediction of fluid flows involving complex free surface motion.

Several automotive examples of SPH simulated HPDC flows are presented, ranging from simple cases such as a front servo piston to steering column components and a full engine rocker cover. These show unprecedented detail in the fluid free surfaces, particularly in the extent of fragmentation and void formation. Validation of isothermal and thermal/solidification predictions are also presented. These results combine to demonstrate that SPH modelling of HPDC has now reached a level where both isothermal and thermal simulations can be performed in reasonable computation times for large scale automotive castings and provide a high degree of predictive accuracy.

INTRODUCTION

High pressure die casting (HPDC) is an important process in the manufacturing of high volume and low cost automotive components, such as automatic transmission housings and gear box components. Liquid metal (generally aluminium) is injected into the die at high speed (50 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 to both product quality and process productivity, including more effective control of the die filling and die thermal performance.

A technique that is particularly well suited to the simulation of HPDC is Smoothed Particle Hydrodynamics (SPH). This is a Lagrangian method for modelling heat and mass flows. Materials are discretised into particles that are able to move around with the governing partial differential equations being converted into equations of motion for these particles. These are really just moving interpolation points that carry with them (convect) physical properties and state information, such as the mass of the fluid that the particle represents, its temperature, enthalpy, density and any other relevant properties, such as stress or strain history dependent rheology. 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 governing equation (e.g. the Navier-Stokes equations).

SPH has been developed over the past two decades initially for astrophysical applications (Monaghan, 1992) and more recently for incompressible enclosed flows (Monaghan, 1994). It is also able to model low-speed incompressible flow (Morris, et al., 1997 and Cummins and Rudman, 1999), viscous flow (Takeda, et al., 1994), underwater explosion (Swegle and Attaway, 1994) and galaxy formation (Hultman and Kallander, 1997). Examples of other applications include heat conduction (Cleary and Monaghan, 1999), natural convection in a cavity and Rayleigh-Benard convective instability (Cleary, 1998) and high pressure die casting (Cleary, et al. 1998, Cleary, et al. 2000).

SPH has several advantages for modelling some classes of industrial heat and mass flows:

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

These advantages make SPH particularly suited to the simulation of HPDC. Recently, Cleary, et al. (2000) and Ha and Cleary (2000) reported on the application of SPH to HPDC in two-dimensions and the favourable comparison of these SPH results with water analogue experiments. It should be noted that particularly good

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resolution of the small scale fluid structures was obtained along with accurate predications of voids in the flow. Ha, et al. (1999) compared SPH simulations with water analogue modelling of gravity die casting for a complex die in two different orientations. The SPH simulations were able to capture the free surface wave behaviour and the fine details of the flow. In this paper, we describe the use of SPH in 3D to predict the filling of several real automotive components.

PREDICTED FILLING OF AUTOMOTIVE PARTS

SPH simulations of the filling of a number of automotive components are presented below. The filling patterns provide information on the order of fill and give guidance about potential sites of porosity formation.

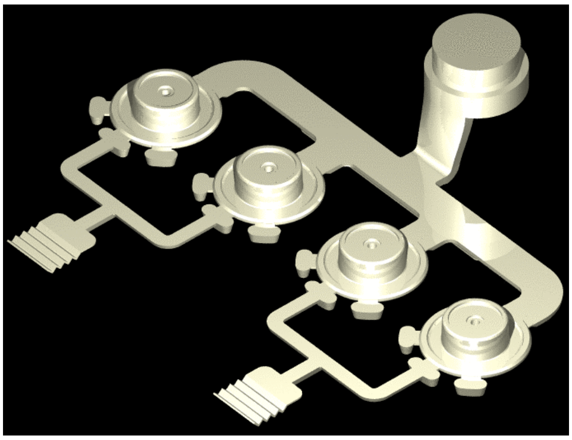

Figure 1: Geometry of front servo piston.

Front Servo Piston

Figure 1 shows the casting configuration for a four part front servo piston. The shot sleeve leads through a converging right angle elbow runner into a chisel gate with a height of 3 mm. The piston head is a fairly simple almost axially symmetric top hat like structure. The base ranges from 0.4 to 0.7 cm in thickness and has a diameter of 11 cm. The diameter of the inner cylindrical structure is 6.4 cm and its height is 3.2 cm. There are three overflow vents on the far side of each piston. The particle size used for the simulation is 1.4 mm. Detailed validation of the SPH predicted fill pattern has been performed for a single such piston by comparing to water analogue experiments and a matching Magmasoft solution (see Ha, et al. 2003).

Figure 2 shows the progress of the fluid front which is coloured by speed, with the maximum being 50 m/s (red) and the minimum being 0 m/s (dark blue). In the first frame, the fluid has just passed through the gates and rapidly moves into the four pitson heads. The fluid fronts are highly fragmented as the fluid splashes across each of the die cavities. The pistons on either end are the first to fill. The incoming stream hits the inside of the annular raised sections and flows around the circular top edges of the pistons. The fluid rapidly reaches the opposite side and blocks the vents, leading to a back flow around the rim of the pistons and around the sides of the top hat. The last locations to fill are directly to either side of the gate. These observations were found to be consistent with the porosity map supplied by the manufacturer.

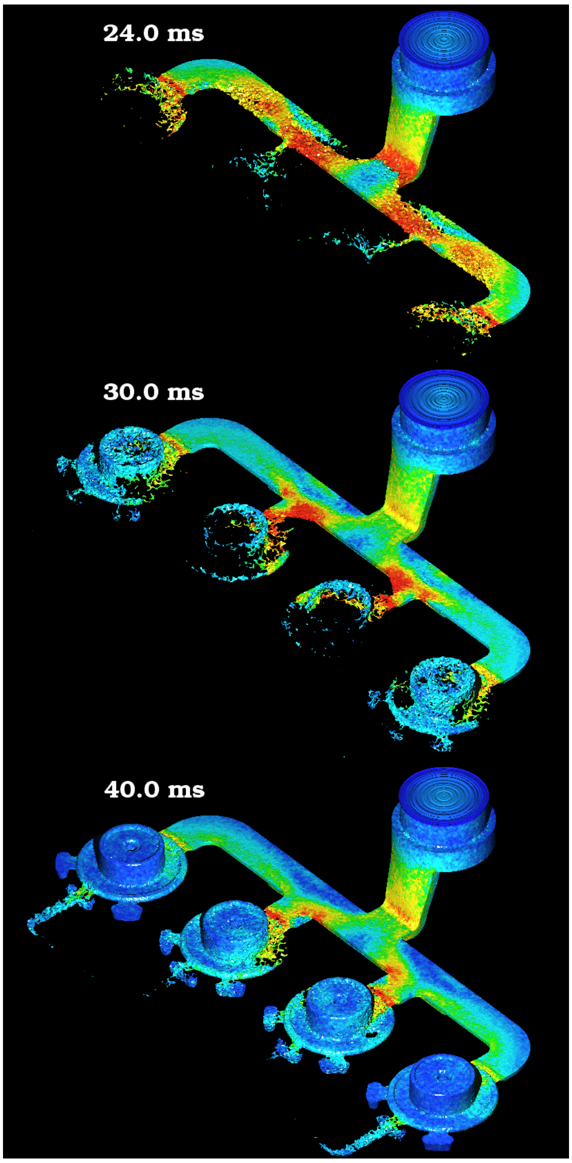

Figure 2: Filling of front servo piston at selected times.

Rocker Cover

Figure 3 shows the casting configuration for an engine rocker cover. It is about 750 mm x 250 mm in area. The section thickness is about 3mm. A tangential runner system feeds fluid through a long gate with a height of 2 mm and gate speed of 12 m/s. The particle size used for this simulation was 1.25 mm.

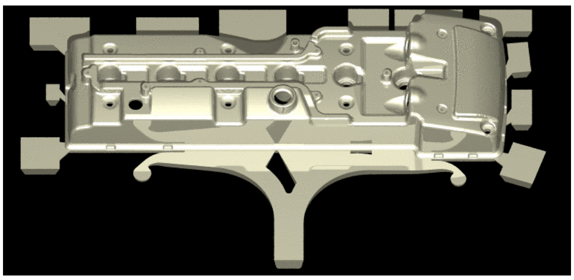

Figure 3: Geometry of rocker cover.

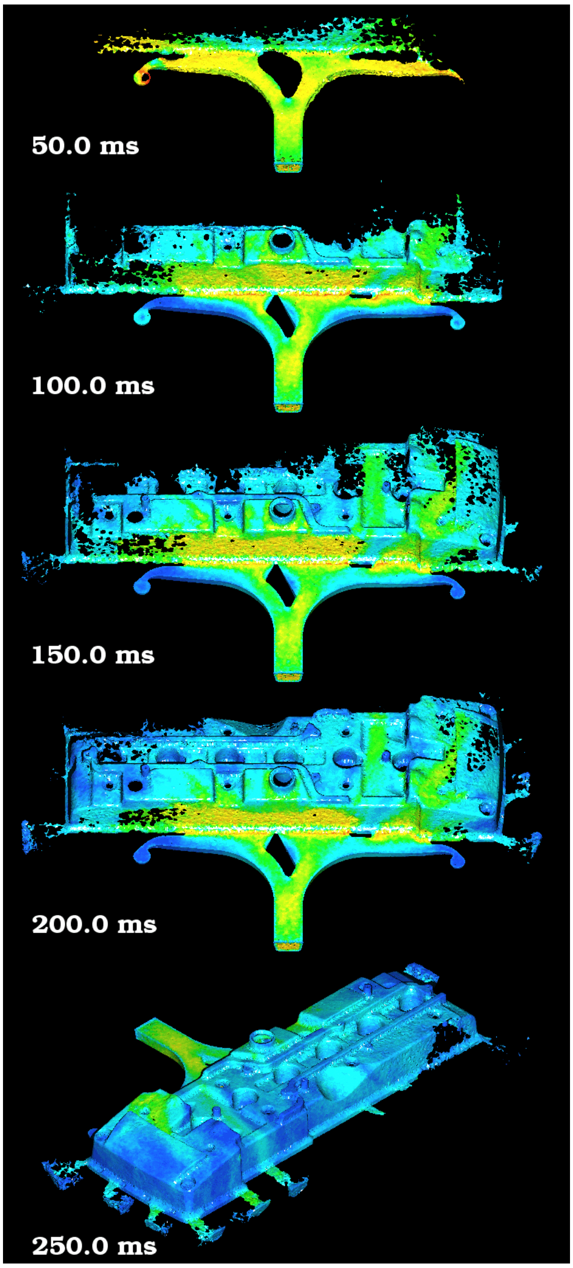

Figure 4: Filling of rocker cover at selected times.

Figure 4 shows the filling of this rocker cover. The long gate has an area that is similar to the runner cross sectional area, so the fluid does not accelarate as much in the gate region in comparison with the previous simulation. This results in somewhat reduced splashing and fragmentation of the fluid upon entry into the die. However, the complex stepped contours of the die lead to long lived void areas. This is essentially the result of the diverging flow from the gate being unable to maintain a uniform front, so fluid is not able to flow into the more protected regions of the die produced by the steps in the shape. Note that there is also clear evidence of preferential race tracking of fluid around the perimeter of the rocker cover. By 250 ms, the die is substantially filled with critical voids remaining in two locations, one just to the side of the gate as seen in the fourth frame of Figure 4 and one on the far side of the casting where recirculating fluid has created a long lived roughly elliptical void (last frame of Figure 4). Again these observations are consistent with observations made by the manufacturer.

Rack and Pinion Steering Column

Figure 5 shows the die and Figure 6 the filling of a component from a rack and pinion steering column. The two cylindrical structures are about 12 cm in length with an inner diameter of 1.25 cm. The simulation uses a particle size of 0.75 mm. The runner consists of two branches, one of which splits into two chisel gates. In this case the fluid attains a high velocity as it reaches the gate region. The fluid fragments and sprays out through the die in a rapidly varying honeycomb like pattern. The fluid reaches the ends of the die and then back fills towards the gates. The volumetric rate of filling through the large gate at the left end of the die is much higher than through the chisel gates on the right, so the left cylindrical section fills much more rapidly. By 20 ms, significant amounts of fluid have flowed up into the vertical cylindrical projection at the junction of the two horizontal cylindrical sections. Some of the external cavity features on the die fill early, as some of the diverging fluid flow is able to flow into them, while others remain unfilled until the end. The last regions to fill in this component are the ones closest to the two gates, as seen in the last frame of Figure 6.

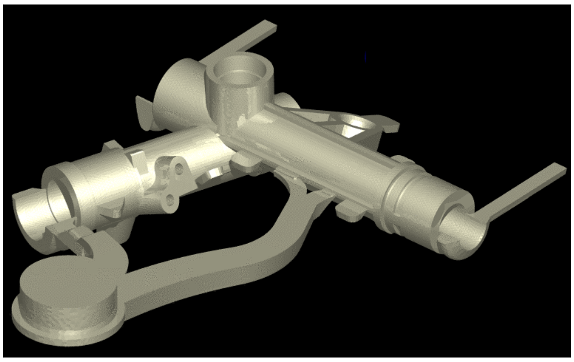

Figure 5: Geometry of steering column.

Cross Member

Figure 7 shows the die and Figure 8 shows the filling of a cross bar support. This part is fairly topologically complex, consisting of several sections with strengthening ribs and various cut outs. There are nine gates distributed along the leading edge of the component and these are fed by a fairly conventional tangential runner system with shock absorbers at the ends. The gate height is 2.6 mm and the particle resolution used for this simulation was 1.7 mm. This die is interesting because of the partitioning created by the significant holes in the part and the high aspect ratio ribs. The fluid sprays out from the gate along clear preferential pathways, leaving regions with long enduring voids on the sides of the central body where insufficient fluid can be supplied by this runner system. By 65 ms, the leading fluid reaches the fair side of the die and much of the structure on the near side of the die is substantially filled. By 91 ms, the entire die is mostly filled, but many areas still exhibit distinct moderate scale voidage. The final area to fill is in the middle of the far side of the die. This is a structurally critical location where porosity is highly undesirable. The simulation shows that despite the presence of a large central bridge which is intended to channel fluid into this region much earlier, this region is difficult to fill and could be subject to cold shuts, joining problems where the fronts of fluid meet from either side and also from trapped porosity.

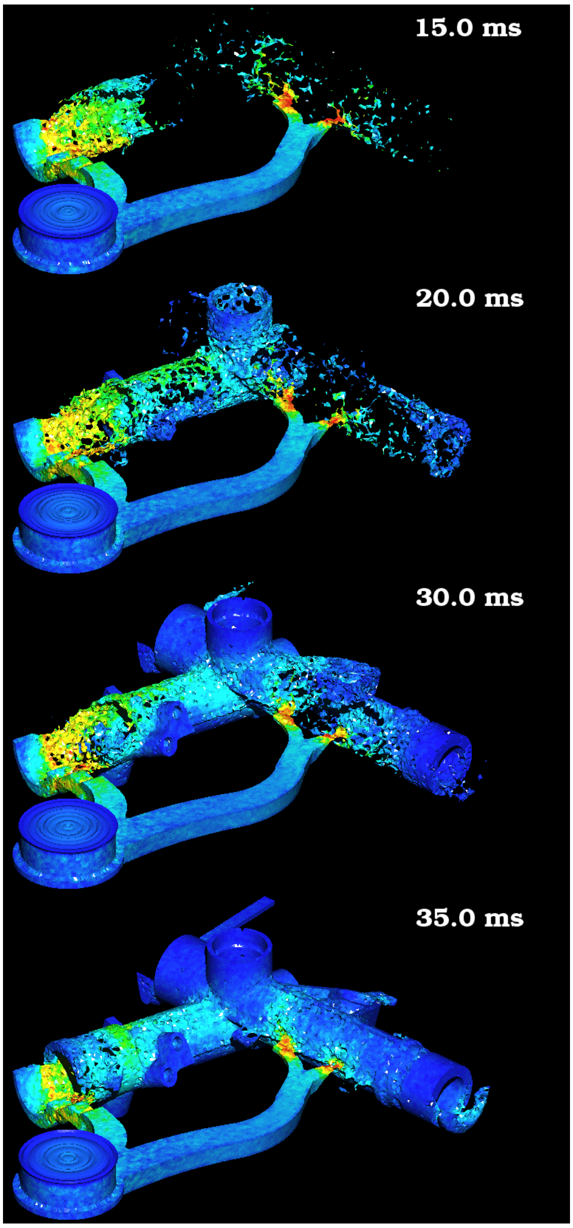

Figure 6: Filling of steering column at selected times.

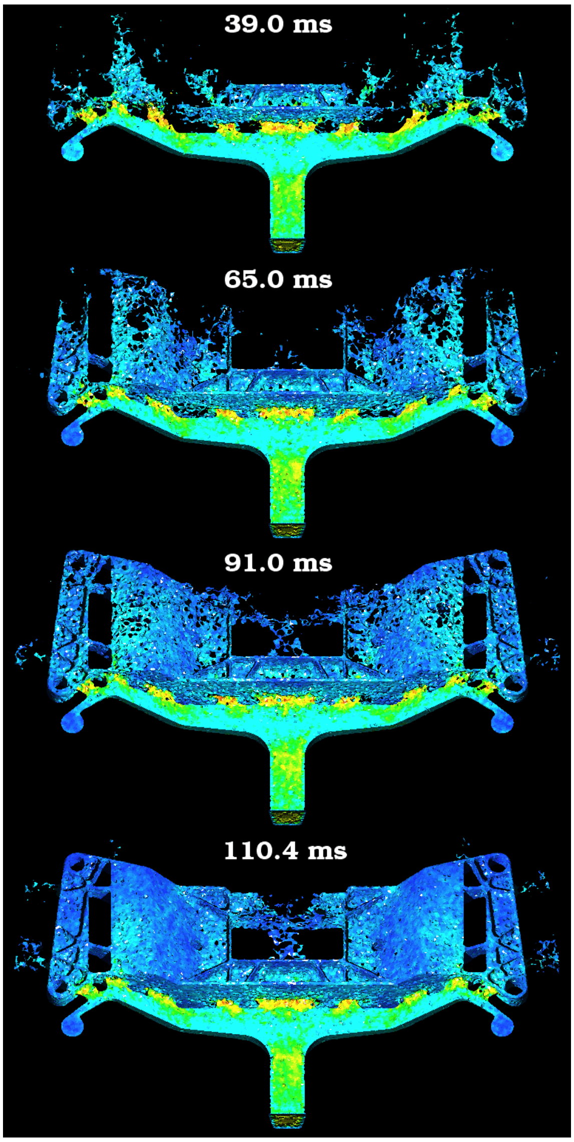

Figure 8: Filling of cross member at selected times.

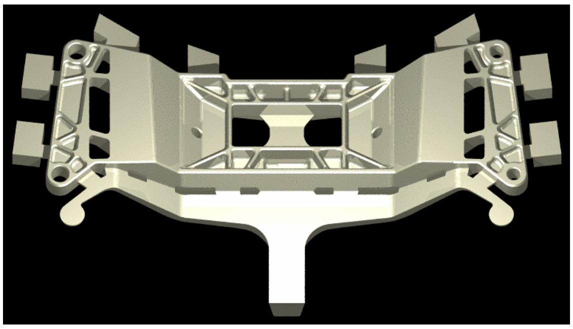

Figure 7: Geometry of cross member.

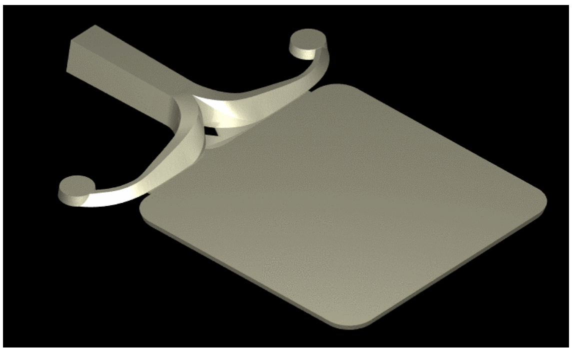

Figure 9: Geometry of coaster.

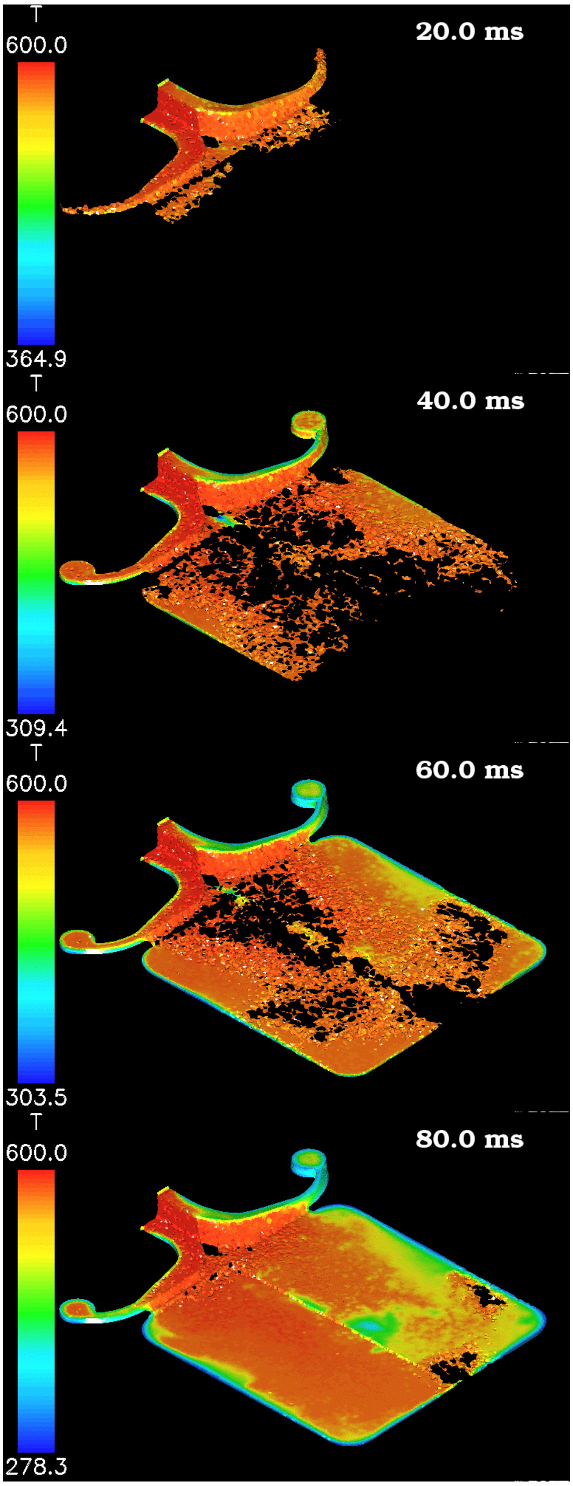

Figure 10: Filling of coaster with fluid coloured by temperature.

Coupled Heat Transfer/Solidification Fluid Flow

To demonstrate and validate the predictions of the coupled thermal, solidification and flow models, a simple thin square coaster with rounded corners (see Figure 9) was simulated. Short shot experiments and matching SPH simulations were performed and are compared here. A tangential runner with a diamond shaped insert in the middle was used. The coaster was 9 cm x 9 cm and 2 mm

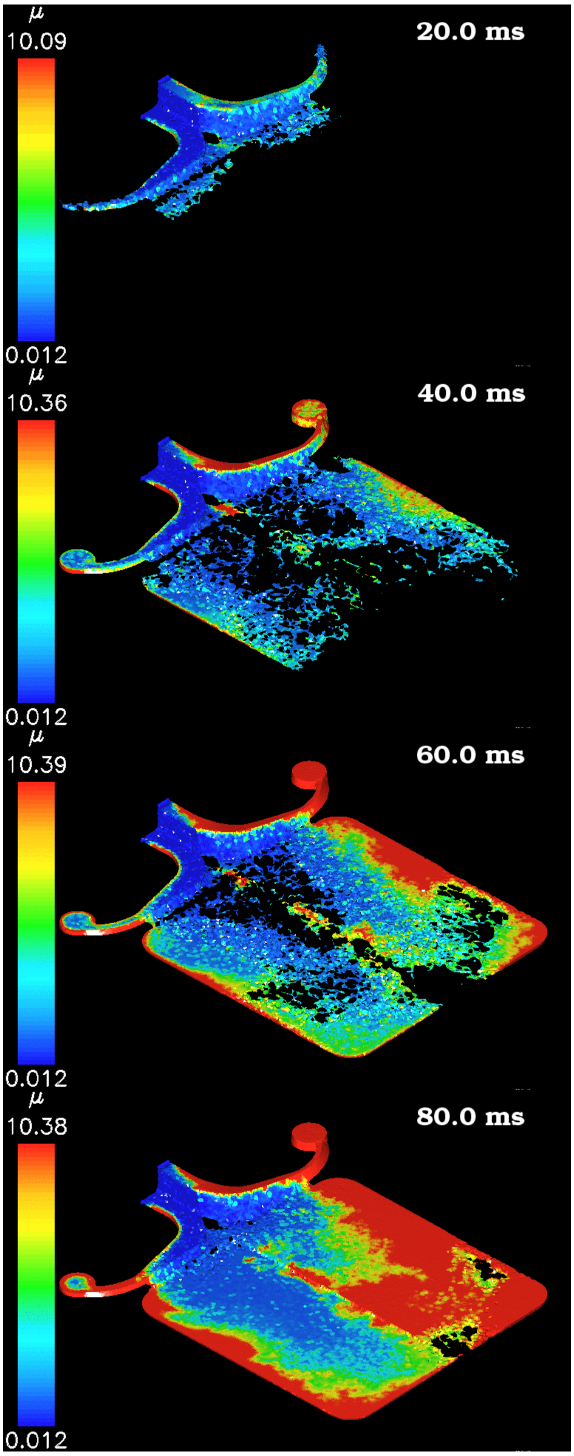

Figure 11: Filling of coaster with fluid coloured by viscosity.

in thickness. The gate was 0.9 mm thick and a particle size of 0.6 mm was used. The simulation used a fully coupled fluid and heat flow model. Conduction was predicted in both the solidifying liquid metal and into and through the die. Temperature dependent material properties, particularly viscosity and the release of latent heat were included. Figures 10 and 11 show the fluid temperature and viscosity respectively during the filling. All the fluid is shown on the right side of the die, so the colouring shows the surface properties. On the left only the material in the bottom half of the die is shown. The temperature and viscosity shown on the top left surface therefore belongs to fluid in the mid-plane of the die. Surrounding the fluid shown here is the solid die, but it is not shown. For the coupled thermal flow, heat conduction from the liquid metal into the die is critical to determine the solidification and therefore viscosity of the fluid. This has a major impact on the predicted fill pattern.

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 high 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. Eventually they do fill in this case, but this casting was close to being a cold shut.

Short Shot Comparison

Short shots are obtained by only partially filling a die cavity, generally by using a smaller shot volume. 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. Figure 12 shows a comparison of an experimental and simulated short shot for the cast aluminium coaster. The simulation is coloured by viscosity, with red being a highly viscous fluid (almost solid). The predicted front profile is in very 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.

CONCLUSIONS

In this paper, we have presented a selection of SPH simulations of automotive components ranging from a simple front servo piston to a rocker cover. The detail in the filling predictions is very high and the last locations to fill correlate well with porosity/voidage observations made by manufacturers of these components. An SPH simulation of die filling of a coaster with fully coupled heat transfer and solidification models was also presented. It showed the additional complexities that heat transfer and solidification play in the die filling process and the possibility of predicting cold shuts. The validity of the heat transfer and solidification models was confirmed by comparing SPH simulated short shots with experimentally obtained ones.

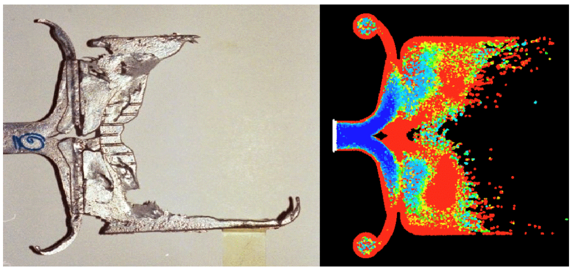

Figure 12: Short shot: experiment (left), simulation (right).

ACKNOWLEDGEMENTS

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REFERENCES

CLEARY, P.W. (1998). Modelling confined multi-material heat and mass flows using SPH. *Applied Mathematical Modelling*, **22**, 981–993.

CLEARY, P.W., HA, J., & AHUJA, V. (2000). High pressure die casting simulation using smoothed particle hydrodynamics. *Int. J. Cast Metals Res*, **12**, 335-355.

CLEARY, P.W., HA, J., MOONEY, J., & AHUJA, V. (1998). Effect of heat transfer and solidification on high pressure die casting, *Proc. 13th Australasian Fluid Mechanics Conference*, Melbourne, Australia, 679–682.

CLEARY, P.W. & MONAGHAN, J.J. (1999). Conduction modelling using smoothed particle hydrodynamics. *J. Comp. Phys*., **148**, 227–264.

HA, J. AND CLEARY, P.W. (2000). Comparison of SPH simulations of high pressure die casting with the experiments and VOF simulations of Schmid and Klein. *Int. J. Cast Metals Res*, **12**, 409-418.

HA, J., CLEARY, P. W., ALGUINE, V. AND NGUYEN, T. (1999). Simulation of die filling in gravity die casting using SPH and MAGMAsoft, *Proc. 2nd Int. Conf. on CFD in Minerals & Process Industries*, Melbourne, Australia, 423–428.

HA, J., CLEARY, P. W., PRAKASH, M., ALGUINE, V., NGUYEN, T. AND SCOTT, C. (2003). SPH, MAGMAsoft and water analogue modellings of die filling of a servo piston, *Proc. 3rd Int. Conf. on CFD in Minerals & Process Industries*, Melbourne, Australia.

HULTMAN, J. AND KALLANDER, D. (1997). An SPH code for galaxy formation problems: presentation of the code, *Astron. Astrophys*., **324**, 534-548.

MONAGHAN, J.J. (1992). Smoothed particle hydrodynamics. *Ann. Rev. Astron. Astrophys*., **30**, 543-574.

MONAGHAN, J.J. (1994). Simulating free surface flows with SPH. *J. Comp. Phys*., **110**, 399-406.

SWEGLE, J.W. AND ATTAWAY, S.W. (1995). On the feasibility of using smoothed particle hydrodynamic for underwater explosion calculations, *Comput. Mechanics*, **17**, 151.

TAKEDA, H., MIYAMA, S.M. AND SEKIYA, M. (1994). Numerical simulation of viscous flow by smoothed particle hydrodynamics, *Prog. Theoretical Physics*, **92**, 939-960.