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SPH MODEL APPROACH USED TO PREDICT SKIN INCLUSIONS INTO SEMISOLID METAL CASTING

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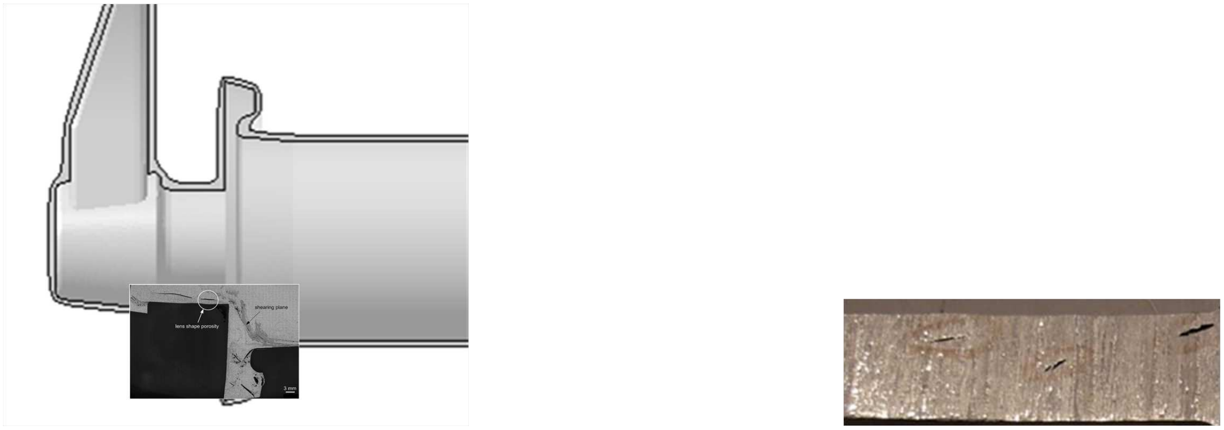
Abstract

Semisolid metal processing of metallic alloys takes advantage of the thixotropic behavior of material with non-dendritic microstructure to produce near-net-shape components with improved mechanical properties. The much higher apparent viscosity of the semisolid billet limits the risk of oxide formed on the free surfaces to become incorporated into the casting during the process. But, the external-skin on the periphery of the billet, which is often partially solidified and contaminated with lubricants, should not be included into the casting as this can be a cause of reject for most structural parts. In this paper, a preliminary model is set-up using the LS-DYNA SPH formulation to follow the paths of the skin. Calculations carried out show that this approach appears to be very promising to predict the paths of contaminated skins into semisolid castings. It can then be utilized to design suitable molds and gating systems.

Introduction

Semi-solid metal processing is an appealing technology to produce near net shape structural components by high pressure die casting. In this process, an alloy is injected into a mold cavity at a temperature lying between the liquidus and solidus so that, in this temperature range, the material appears as a dense suspension of liquid and solid metal with particular rheological properties. In general, on a short time scale, semi-solid metals are characterized by a shear thinning behavior[1] though shear tickening behaviors have also been reported in the litterature e.g. ref. [1]. When there is no relative motion between the particles, the material acts as a solid but when sheared, the bonds between the particles are locally broken and the material starts to flow. This particular behavior can be exploited to fill mold cavities in a progressive manner, thus cutting down on splashing as well as on gas, oxides and surface skin entrapment. This process permits to produce parts with low porosity and uniform microstructure, which can then be heat treated to obtain superior mechanical properties (high strength and good ductility), suitable for instance to the production of structural applications in the automotive industry.

[1]on longer time scales much greater than those found in die casting processes, the material is thixotropic



(a) created along a shearing plane (b) in the casting

Figure 1: Porosity lens defects

Semi-solid metal slurries are obtained by stirring the alloys during solidification in order to produce a “semi-solid” billet having a non-dendritic solid phase within a liquid metal matrix. During the preparation of this billet and subsequently during its transfer into the shot sleeve, the metal surfaces that are in contact with air as well as with the container walls form a “skin” around the semi-solid core. Moreover, when inserted horizontally into the shot sleeve, the contact between the bottom part of the billet and the shot sleeve wall is stronger because of gravity. As a result, the heat transfer is enhanced there and yields a partially solidified skin-layer. Most of the lubricant in the shot sleeve lies at its bottom and thus touches the external lower surface of the billet. When injected into the cavity, these contaminated surfaces may enter into the part, (figure 1a), and yield undesired defects like oxide film inclusions and lens shape porosities resulting from the decomposition of lubricant during the heat treatment, (see figure 1b).

To prevent inclusion of potential defects in structural semi-solid cast parts, entrainment of the skin surrounding the billet into mold cavities must be predicted and properly controlled. Since experimental observations and probing for such partially molten material are difficult to perform, because of the extreme conditions of temperature and pressure, numerical simulations is employed to “virtually” investigate the process. In the last several decades, the latter have played a valuable role in the analysis and understanding of such complex phenomena associated with the movement of solidifying metal. Several of these numerical models consider that the semi-solid material can be approximated as a one-phase material e.g. [2]. By using appropriate shear rate dependent constitutive laws, it is possible to predict reasonably well the die filling behavior in terms of flow front for many applications. However, in the latter approaches, the pressure is not reproduced correctly which means that something is missing. Indeed, semi-solid slurries are two-phase mixtures of liquid and solid particles. When correctly accounted for, the physics of semi-solid mixture does reveal additional complex phenomena such as phase segregation e.g. [3] and shear bands e.g. [4] which effectively affect the behavior of the bulk material. Such a shear band is depicted in figure 2 where very complex phenomena like grain packing on the shot sleeve end side (bottom), expelled liquid from the flowing material side (top) and relative sliping of the two regions on one another. The physics which governs the formation of shear bands is discussed for instance in references [5]. The occurrence of those shear bands enriched with eutectic inside the shot sleeve possibly contributes to the skin inclusion problem in semi-solid parts.

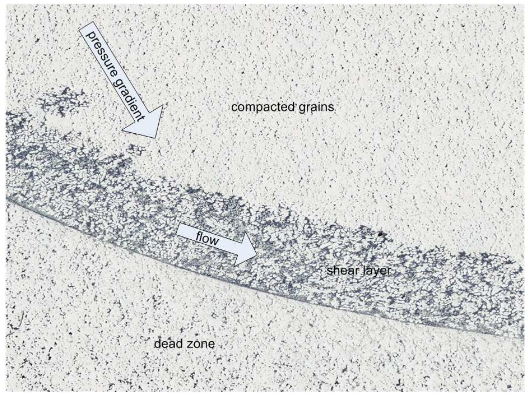


Figure 2: shear layer

So far, semi-solid metal flow modelling remains quite challenging as the flow behavior is a function of microstructure, temperature, solid fraction, state of agglomeration between the particles and segregation between the solid and liquid phases. Most of these features depend on the temporal effect of the shear rate on each bundle of particles in the slurry. The skin properties are likely to depend on where and for how long its surface has been in contact with walls and contaminants and might be different from the properties of the core of the billet. The behavior of each bundle of the solid/liquid particles thus depends on its history in the moving flow.

This kind of problem is easier to deal with using Lagrangian methods. However, treatment of large deformation as the ones encountered in semi-solid flows is very tedious with grid base methods. A strong interest is now focused on the development of Lagrangian mesh free approaches like the "Smooth Particle Hydrodynamic" (SPH) method for modelling fluid flows. This scheme was initially developed by Lucy [6] and Gingold and Monaghan [7] in order to solve astrophysical problems in three-dimensional open spaces. Besides the meshfree and adaptive nature of the method, the particles in SPH carry their own material properties which make the method highly suitable to represent metallic slurries during semi-solid injection processes. The method has already been successfully applied to predict the oxides generated by several casting pouring processes eg.[8, 9].

This paper is a follow-up of the initial steps for the development of a Smooth Particle Hydrodynamics (SPH) model for semi-solid metal casting that were presented elsewhere [10]. The aim of this preliminary work using an isothermal Newtonian high viscosity fluid is to assess the potential of the method for the design of efficient runners and gating systems for semi-solid processes.

Modelling

In the smooth particle hydrodynamics method, the state of the system is represented by a set of particles, which possess individual material properties and move according to the conservation equations. In addition to their role of interpolation points, SPH particles also carry material properties which means that they act as both approximation points and material components. Basically, the SPH method consists of two key tasks. The first one is the integral representation of the function $< A(r) >$ where the product of an arbitrary function and a smoothing kernel function is integrated such as (for details, see Liu and Liu, 2003 [11]):

$$< A(r) >= \int_{\Omega} A(r')W(|r - r'|, h)\, d\Omega \tag{1}$$

where W is the smoothing function and h is the smoothing length which determines the influence domain of the smoothing function.

Equation (1) is then approximated by summing up the values of the nearest neighbor particles, which yields the particle approximation of the function at a discrete particle:

$$A(r) = \sum_j A_j \frac{m_j}{\rho_j} W(r - r_j, h) \tag{2}$$

$$\nabla A(r) = \sum_j A_j \frac{m_j}{\rho_j} \nabla W(r - r_j, h) \tag{3}$$

Using equations (2) and (3) the governing equations for mass and momentum conservation are obtained:

$$\frac{\partial \rho_i}{\partial t} = \sum_{j=1}^{N} m_j \nu_{ij} \frac{\partial W_{ij}}{\partial x_i} \tag{4}$$

$$\frac{\partial v_i}{\partial t} = \sum_{j=1}^{N} m_j \left(\frac{\sigma_i}{\rho_i^2} + \frac{\sigma_j}{\rho_j^2} \right) \frac{\partial W_{ij}}{\partial x_i} \tag{5}$$

where σ_i and σ_j are components of the stress tensor at particle i and j respectively obtained with the constitutive equation. ν_{ij} is the relative velocity vector between particles i and j.

The pressure is obtained using a linear polynomial equation of state (EOS):

$$p = K \left(\frac{\rho}{\rho_o} - 1 \right) \tag{6}$$

where ρ_o is the reference density and K is a constant.

The discrete SPH equations can then be integrated with standard methods e.g. ref. [11].

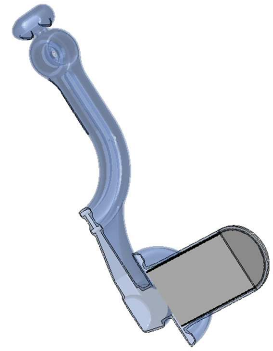
Problem setting

The problem considered in this paper is the casting of an aluminum suspension arm by semi-solid metal processing. The "as cast" component is depicted in figure 3a. The removal of the oxide skin takes place in a concentric annular reservoir which is located between the casting chamber and the mold [12]. The equivalent SPH model includes the shot sleeve, the billet, the plunger and the mold inner surfaces as depicted in figure 3b.

At time t_0, the shot sleeve is completely filled with semi-solid material. The remaining volume of the cavity is empty. The skin of the billet is identified on the cylindrical outer surface by dark particles. In this preliminary study, the skin possesses the properties of the core of semi-solid aluminum. Actually, these properties should be different because of partial solidification and contamination due to contact with the wall.

Newtonian flow behavior is assumed with the viscosity set to 1.0 x 10^{-3} MPa.ms. The problem is considered isothermal with a material density of 2.67 mg/mm^3 . About 125000 SPH particles have been used for the simulation. For this example, the plunger velocity is 1 mm/ms.

(a) actual part



(b) SPH model

Figure 3: suspension arm

Results and discussion

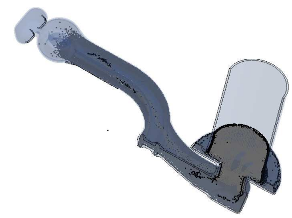
Simulations have been done using the non-linear explicit code LS-DYNA. Figure 4 shows the filling sequence of a single ring type oxide remover for different filling times. The aluminum core is grey and the skin is represented by black particles. While the billet is pushed against the end face of the cold chamber, its inner portion is extruded through the orifice and makes its way to the feeding channel. The outer portion is pushed radially outward through the cylindrical opening and is collected in the ring shape reservoir. The skin accumulates there as long as the reservoir is not completely filled. When the oxyde ring is full, the skin turns inward and enters into the feeding channel. The amount of skin that goes into the part then depends on the amount of aluminum that remains in the shot sleeve at the end of the plunger stroke. During the whole process, the skin is pushed against the wall and remains close to it. This is a consequence of the Newtonian flow model employed. As mentioned previously, the flow is actually non-Newtonian with shear banding effects, e.g. [5]. The liquid-solid mixture has rheological behavior dependent on the deformation conditions, on the partially solid microstructure as well as on the segregation of phases. All these can induce a material instability which can promote the inclusion of the skin toward the center of the flow somewhere upstream in the cold chamber and facilitate its propagation into the casting (like in figure 1a).

Note that the fluid fronts are fragmented during the filling of the arm. At this time, it is not clear if this is completely right. Depending on the process conditions, some jetting may occur but usually, semi-solid fluid fronts are rather sharp. As already mentioned, the model used here is very simple. A more complex model has to be developed in order to completely validate the flow of semi-solid material. Figure 5 depicts the movement of the skin surface represented by the outer particles. The core of aluminum has been removed to facilitate visualization. These results suggest that with this configuration, some skin fragments injected at the end of the plunger stroke can propagate far downstream and can initiate defects into the part. The geometry has to be optimized to catch most of the skin before it goes into the feeding channel. An interesting point here is that some of the skin accumulates in the contraction vein preceding the orifice. Experimental evidence of this phenomena is shown in figure 6a where the combined flow/solidification/surface contamination has made the inner "flowing" section to completely separate from the outer "stationary" section of the biscuit. The contaminated surface produced a sharp and brittle interface with the biscuit, which easily broke from the casting. If this section were cut on the plane of symmetry, the "clean" metal in the central line connecting the channel and the shot sleeve area would have

(a) 65 ms

(b) 90 ms

(c) 115 ms



(d) 130 ms

Figure 4: filling sequence, single ring

(a) 65 ms

(b) 90 ms

(c) 115 ms

(d) 130 ms

Figure 5: skin prediction locations, single ring

prevented the part separation. The simulation results suggest that this feature could be possibly predicted by the SPH model (see figure 6b).

Figure 7 depicts the filling of the same suspension part with a triple ring configuration. In this case, practically all the skin is collected into the concentric reservoir and the part is virtually free from defects.

These preliminary results obtained with a very simple SPH model are encouraging. They show that this approach has the potential to predict the skin propagation phenomena in semi-solid processes. Since the SPH method also permits to represent the very complicated physics of semi-solid materials such as multiple phases, realistic equation of state, solidification, fracturing, porous media flow and history dependence of material properties, it is foreseen that this approach will greatly improve the knowledge of semi-solid flows in a very next future.

(a) experimental (b) SPH model

Figure 6: semi-solid material separation due to a shear layer

(a) 65 ms (b) 90 ms

(c) 115 ms (d) 170 ms

Figure 7: skin prediction locations, triple ring

Conclusions

The aim of the present work was to verify the potential of the SPH method to model semi-solid casting. As mentioned before, the SPH method is particularly well suited to model complex flow behaviors like the ones found in semi-solid materials. Indeed, in the SPH approach, materials are approximated by particles that are free to move around, enabling the modeling of materials for which time-history is important. In this preliminary work, an isothermal constant viscosity model has been used. Of course, this simple model does not yet reproduce the full complex semi-solid behavior of an aluminum alloy but nevertheless, the results presented here appears to be very promising. To obtain more realistic quantitative results, the next steps would be to include non-Newtonian flow behaviors in the model with fully coupled heat transfer and solidification capabilities. The additional complexities that heat transfer and solidification play in the semi-solid die filling process will help in the understanding of such complex flows.

As for the preliminary results concerning the process itself, the concepts for oxide removal depicted in reference [12] investigated in the present study show that for the single ring configuration, the device appears to work well as long as the reservoir is not completely filled. Afterward, the skin is free to enter into the feeding channel. It is also shown that most of the skin is injected into the feeding channel at the end of the plunger stroke. This suggests that the use of a longer biscuit would reduce the probability of skin inclusion into the mold cavity. The use of three concentric rings instead of one appears to catch the totality of the skin. More convincing results are expected with a more sophisticated model.

Acknowledgments

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References

[1] D. H. Kirkwood, M. Suéry, P. Kapranos, H.V. Atkinson, and K.P. Young. *Semi-solid Processing of Alloys*. Springer-Verlag, New York, 2010.

[2] M. Modigell and L. Pape. One phase fluid dynamics modelling (Chapter 3). In H.V. Atkinson, editor, *Modelling of semi-solid processing*, pages 51–76. Shaker-Verlag, Aachen, 2008.

[3] J. Petera. Two phase approach to modelling of semisolid processes (Chapter 4). In H.V. Atkinson, editor, *Modelling of semi-solid processing*, pages 77–103. Shaker-Verlag, Aachen, 2008.

[4] F. Pineau and G. Simard. Investigation of the primary phase segregation during the filling of an industrial mold with semi-solid a357 aluminum. *Solid State Phenomena*, 141–143:635–640, 2008.

[5] C.M. Gourlay and A.K. Dahle. Dilatant shear bands in solidifying metals. *Nature*, 445(4):70–73, 2007.

[6] L.B. Lucy. Numerical approach to testing the fission hypothesis. *Astronomical Journal*, 82:1013–1024, 1977.

[7] R.A. Gingold and J.J. Monaghan. Smoothed particle hydrodynamics: Theory and application to non-spherical stars. *Monthly notices of the royal astronomical society*, 181:375–389, 1977.

[8] P. Cleary, M. Prakash, M. Sinnott, J. Grandfield, V. Alguine, and K. Oswald. Validation of sph predictions of oxides generated during al melt transfer. In *Proc. of the 7th International Conference on CFD in the Minerals and Process Industries*, pages 1–6, Melbourne, Australia, 2009. CSIRO.

[9] M. Prakash, P. Cleary, and J. Grandfield. Modelling of metal flow and oxidation during furnace emptying using smoothed particle hydrodynamics. *Journal of Material Processing Technology*, 209:3396–3407, 2009.

[10] F. Pineau and G. D'Amours. Application of ls-dyna sph formulation to model semi-solid metal casting. In *Proc. of the LS-DYNA 8th European Users Conference*, Strasbourg, France, 2011. Alyotech.

[11] G.R. Liu and M.B. Liu. *Smoothed Particle Hydrodynamics, a meshfree particle method*. World Scientific Publishing Co. Pte. Ltd., Hackensack, N.J., 2003.

[12] E Röllin, H. Huber, and J-P. Gabathuler. Oxide remover, u.s. patent 5,730,201, March 1998.