Tracking Defects

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ABSTRACT

Many defects observed in castings originate from surface contamination that has been entrained into the body of the part. Surface contamination may arise from several sources including loose sand, oxides and, in the case of lost foam casting, residue from vaporized polystyrene.

Entrapment of surface defect material into the interior of a casting results from the meeting of two fronts (folds or laps) and by surface turbulence at the front. Once residue is trapped it continues to move with the flowing metal and may be diluted and dispersed to locations far removed from its origin.

In this paper a defect source and tracking scheme is described that gives a qualitative prediction of surface oxide defects. The defect model has also been coupled with Lost Foam casting simulations to predict possible defects arising from carbon residue remaining on metal surfaces after the foam has been evaporated.

Defects, or at least the likelihood of defects, are represented by a scalar variable that is initially zero everywhere. Sources for the scalar are then defined to represent surface oxide formation or foam residue. The scalar flows with the metal using a second order, monotonicity-preserving numerical scheme for increased accuracy. At the end of a simulation the probability distribution of defects is proportional to the magnitude of the scalar variable.

Several examples are presented to show the type of information that can be obtained with this model. Even the simplest of test cases reveals a considerable amount of useful insight into the processes responsible for defect generation and their final distribution in a cast part.

Introduction

Mechanical properties of the final casting may strongly depend on the “cleanness” of the metal with regards to oxide films, air and other foreign inclusions that are likely to get trapped inside the metal during the filling process. For surface contamination to be directly entrained into a body of metal there must be sufficient kinetic energy in the flow to produce local overturning of the free surface, as shown in Figure 1. This concept, termed "surface turbulence" by Professor John Campbell of Birmingham University, has been shown to have significant consequences on the quality of cast Aluminum parts (Fig. 2) [2]. Figure 3 shows examples of internal porosity defects resulting from trapping air during a high pressure filling process of a wiper housing part.

In this paper a defect source and tracking scheme is described that gives a qualitative prediction of casting defects originating from surface turbulence. The defect model has also been coupled with a lost foam casting model to predict possible defects arising from carbon residue remaining on metal surfaces after the foam has been decomposed.

Model Description

Surface inclusions are represented by a scalar variable that is initially zero everywhere. In the oxide-tracking model, the scalar quantity accumulates at free surfaces at a constant rate. When coupled to the lost foam model, the scalar quantity in a numerical control volume is incremented by an amount proportional to the mass of degraded foam in that volume. This scalar is then allowed to advect with the flow. A transport equation is solved numerically using a second order, monotonicity-preserving scheme for increased accuracy. The scalar may be interpreted as proportional to the mass of contamination material per unit volume.

At this point no buoyancy and oxide film strength effects are included in the model. Also not included are such phenomena as oxide film sticking to mold walls and foam residue escape through a porous sand mold.

At the conclusion of a simulation, the distribution of the scalar indicates locations where inclusions are likely to be. In most cases the majority of scalar tracked inclusions are found at the last place to fill, as would be expected. In other words, contaminants accumulate at the metal front and are pushed along until there is no where else for them to go.

More interesting, however, are situations where two fronts meet, trapping surface inclusions in the interior of the metal, or near corners where flow recirculation regions may develop. Even the circulation remaining in metal after a mold has filled can redistribute surface generated contaminants.

Without detailed experimental comparisons to correlate predictions from this type of model with actual defects, it is impossible to assign any significance to the absolute values of the scalar. However, qualitative results from even the simplest of test cases reveals a considerable amount of useful insight into the processes responsible for defect generation and their final distribution in a cast part.

In the following sections we shall give a few examples of what can be learned. Simulations are carried out using the commercial CFD code ***FLOW-3D***® [3], where the surface contaminant model has been implemented.

Defect Prediction and Plastic Weld Seams

Tadmor and Gogos give a simple, nearly two-dimensional, example of weld seam generation for a case of plastic injection molding [4]. The mold consisted of a long narrow slab with a combination of rectangular and circular obstacles in its interior. Plastic enters the slab at one end through a small gate and flows around the obstacles as it fills the mold. In the wake of each obstacle there is an indication of where two surfaces have met and then have been drawn downstream with the subsequent flow. A simulation of this experiment was done as a validation test. On a whim, marker particles were placed at the leading edge of the plastic entering the mold. Amazingly, at the end of filling the markers were found to be in good agreement with the experimentally observed weld seam defects, see Figures 4*a*-*b*. A repeat of this computation using the scalar transport concept instead of marker particles shows that the scalar technique is as good or better in some respects than the marker particle method, see Figure 4*c*. The disadvantage of marker particles is that they cannot be subdivided, while the scalar variable has no such restriction. This allows the scalar to give a more continuous estimate of the "probability" of where defects are likely to occur. The scalar method also requires less CPU effort than particles and it is more easily incorporated into displays of other flow quantities.

Defect Prediction in a Lost Foam Casting

The Tadmor mold was converted (computationally) to a lost foam mold and the plastic was replaced by aluminum. The properties for foam and aluminum were taken from Yao and Shivkumar [5].

A pressure inlet condition corresponding to a 0.28 *m* head of metal was defined at the gate. Two snapshots from this simulation are shown in Figure 5, one when the mold is about half full and the other when it is nearly filled. As the foam is degraded, contributions to the scalar at the metal-foam interface are generated at a constant rate.

During filling, the highest concentrations are always observed at the interface, as would be expected. At the end of filling this leads to a high concentration at the location that is filled last. Of more interest, however, are all the other locations where scalar values are observed. For example, we see significant values in the two upstream corners nearest the gate. These values come from material initially pushed into the corners early in the filling period that remain there during the remainder of the filling because the flow is almost stagnant in these regions. The fact that possible defects are trapped and remain in the upstream corners because of stagnant flow is an important observation.

The same thing is happening in the wakes of the obstacles. Behind each one there are some residual scalar values. These values are initially created because of the meeting of metal fronts coming from either side of the obstacles. However, it is also the flow stagnation, and recirculation, in these regions that keeps the scalar values from being mixed into the flow and advected downstream. A closer look at the computed results also reveals that some amount of the scalar quantity gets left along the walls. The initial deposition comes from the metal front and wall shear helps to slow the flow velocity near walls so the scalar can't be diluted as readily from these regions.

The positive correlation observed between computational and experimental data in the case of plastic injection molding offers encouragement for similar defect prediction in the lost foam process. More importantly, observations such as these are not peculiar to this simple example. The advantages of a simulation tool is that it can quantify the creation and subsequent dilution and advection of possible defects throughout the body of cast parts of nearly any complexity.

Surface defect predictions in a rectangular box for different filling processes

Using the defect-tracking model, we can investigate differences in the behavior of surface inclusions for a variety of mold filling methods: low pressure and high pressure filling, lost foam and semi-solid metal processes. For convenience we will apply those filling processes to the same simple two-

dimensional 200 *mm* by 300 *mm* mold with two gates. The metal is A356 aluminum.

Low pressure filling. In the low pressure filling, the air pressure inside the mold cavity is slowly decreased to ensure smooth flow with minimal splashing and oxide film entrapment. The filling time is 5.0 *sec*. The simulation results show that, indeed, free surface shape remains primarily horizontal, with no wave overturning or jetting. However, we observe a different mechanism for oxide entrainment. Four large circulation zones form on each side of the gate and pull the oxide away from the free surface and walls into the bulk of the liquid metal, as shown in Figure 6*a*.

In can also be observed that smaller gates and faster filling rates increase the likelihood of oxide entrainment. In the second example of low pressure filling we used a three times larger gate area, maintaining the same filling rate. Figure 6*b* shows that the circulation zones in the box are reduced dramatically keeping most of the oxide at the surface.

One can conclude that it is not just the smoothness of the free surface that reduces oxide film entrapment. It is equally important to eliminate flow separation and recirculation in the bulk of the metal.

Lost foam casting. Here we fill the box with polystyrene before filling. A constant pressure head is maintained at the gates during filling equal to twice the height of the cavity. The filling rate is primarily controlled by the metal/foam heat transfer coefficient. The filling time is 8.5 *sec*. The scalar variable during the lost foam filling process represents foam residue.

The lost foam filling method typically produces very smooth advance of the metal front. Jetting, splashing and wave overturning are practically eliminated as can be seen in Figure 7*a*. In fact, the metal front behavior resembles that of a very viscous fluid. However, there is significant internal circulation of metal due to its low viscosity, which generally distinguishes the flow pattern in a lost foam filling process from the flow of a real viscous fluid. Consequently, the foam residue distribution is affected by that circulating flow, similar to the low pressure filling process described above (Figure 7*b*).

The accumulation of residue along the vertical plane midway between the two gates is a consequence of two metal fronts meeting and trapping the residue, forming a characteristic seam line. In addition, the two converging metal streams near the metal/foam interface bring more contamination to the seam line location. Significant amount of residue gets trapped in relatively stagnant areas at the bottom of the box near the gates. In real conditions, some of the surface residue would escape through the coating and porous mold walls.

High pressure filling. In this case, the mold is filled very quickly, in 40 *msec*. The gate velocity is 40 *m/sec*. The flow is characteristically turbulent, with significant jetting and splashing of the metal. As a result, air bubbles are trapped in the bulk of the metal, away from the mold walls as shown in Figure 8*a*. As more metal enters the cavity, the bubbles shrink and eventually disappear. Although the pressure in each bubble increases with the reduction of its volume, bubbles disappear due to the fixed flow rate at the gates and a finite mesh resolution. The primary interest for pressure die casters is to know where these bubbles form and where they collapse at the end of filling.

The scalar variable forms on every element of the multiple free surfaces. The largest concentrations at the end of filling are at the places where trapped bubbles collapse (five locations, Figure 8*b*). The scalar variable distribution can be interpreted as proportional to the amount of trapped oxide and dissolved air in the metal.

Curiously, the largest concentrations of oxide in the high pressure filling process occur at locations close to where the *lowest* concentrations are in the low pressure filling process (see Figure 6).

Semi-solid metal casting. For this simulation we use a time dependent rheological model of semi-solid metal, in which the steady-state viscosity is a function of strain rate [6]. Material properties for A357 are taken from Quaak for the solid fraction equal to 0.54 [7]. The filling rate in this case is 1/10 of that for the high pressure filling, with the gate velocity set at 4 *m/sec*.

Due to the large viscosity of the metal (the Reynolds number is about 0.01 and the Galileo number is less than 0.0001), the flow is very smooth, with no splashing or jetting. The characteristic feature of the flow is the folding of the two metal streams emerging from the gates as they hit the top wall, similar to the 'bending' of the tooth paste when it impinges on a flat surface (Figure 9*a*). Such flow behavior defines a multi-layer distribution of the surface oxides in the metal at the end of filling, as shown in Figure 9*b*, which may be typical of the semi-solid metal flow due to the high viscosity of the fluid.

The entrainment of the oxides occurs primarily when two or more metal fronts merge. Since the metal in the SSM process is already partially solidified, ensuring sound mechanical bond between two metal surfaces may be problematic.

Wiper Housing Simulation

For a more rigorous test of the defect tracking model, a real casting of a automotive wiper housing was selected. The part was produced by the high pressure die casting process and showed significant porosity due to entrapped air (Fig. 3). The geometry of the die cavity, including the feeding system and

overflows, is shown in Figure 10. The filling time is about 55 *msec*.

The defect tracking model was employed during the filling simulation, together with the back pressure model. The latter tracked each air bubble in the die cavity and computed the bubble pressure as a function of its volume according to $pV^{\gamma}=const$, where $\gamma=1.4$ is the ratio of the specific heats for air.

Figure 11 shows trapped air bubbles in the die cavity at 60% fill fraction. Most of the air is trapped near the gates, which is typical for the high pressure filling process. Figure 12 shows an array of air bubbles and the inclusion distribution at 90% fill fraction predicted near a section of the casting where surface porosity was found in the actual part. Figure 13 shows the distribution of the defect concentration through a cross-section where porosity was also found in the part.

The predicted locations of the defects due to trapped air and oxides correlate well with the porosity defects in the actual part. The defect tracking model offers a convenient way of analyzing the quality of a filling process by capturing the locations of the trapped surface inclusions in the final frame of the filling process. Previously, many subsequent frames of the filling simulation results would have to be viewed to see the detailed evolution of the air bubbles and locations of their collapse and entraiment.

Conclusions

According to a METAL newsletter article, more than 80% of casting defects in aluminum and steel castings can be related to the entrapment of a surface contaminant, such as oxide or slug [8].

A simple model for tracking contaminating materials that form on the surface of liquid metal has been demonstrated to be a powerful tool for predicting defects that result from the entrainment of these contaminants into metal bulk during mold filling. The distribution of the inclusions in the metal can be interpreted as the probability of the defect occurrence: larger concentrations denote larger probabilities.

Coupled with the accurate fluid flow and free surface tracking algorithms of ***FLOW-3D***® and using its library of physical models, the new surface contaminant model provides insights into the details of mold filling during various casting processes. Process conditions, gating and runner designs can be optimized to reduce the likelihood of defect occurrence.

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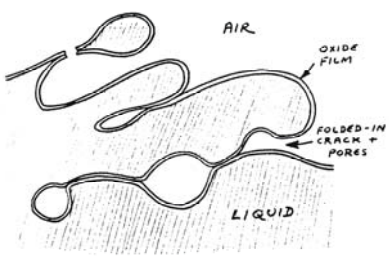

Figure 1. "Surface turbulence" mechanism of entrapping oxide films and air [1].

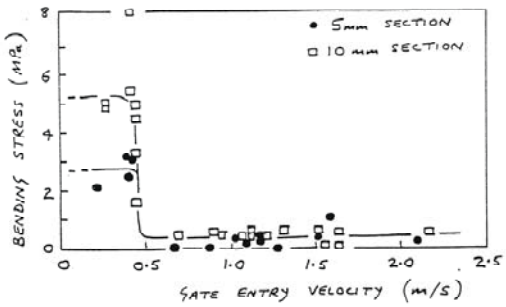

Figure 2. Mechanical strength dependence on the gate velocity for an aluminum plate casting. The gate velocity translates into the amount of oxide film entrapped during filling [2].

Figure 3. Examples of surface (left) and internal (right) casting defects arising from oxide film and air entrapment during a high pressure die casting of an aluminum wiper housing component.

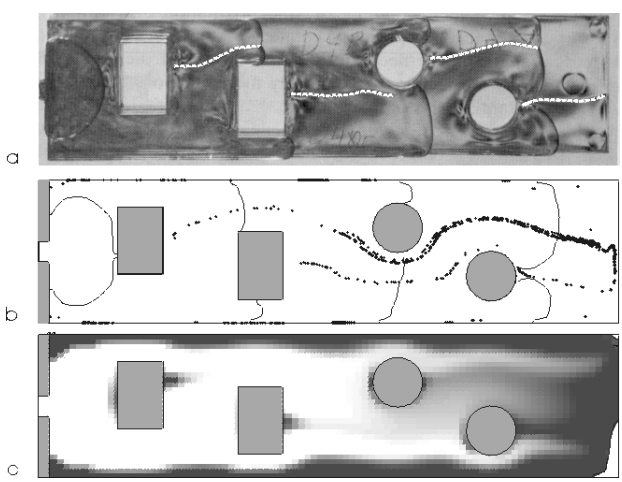

Figure 4. 2-D plastic injection results: (*a*) experimental data shows seam lines (white dashed lines) and free surface location at different times during filling [3]; (*b*) simulation results using marker particles to show the location of seam lines; (*c*) simulation results using a continuous scalar variable to model the seam lines.

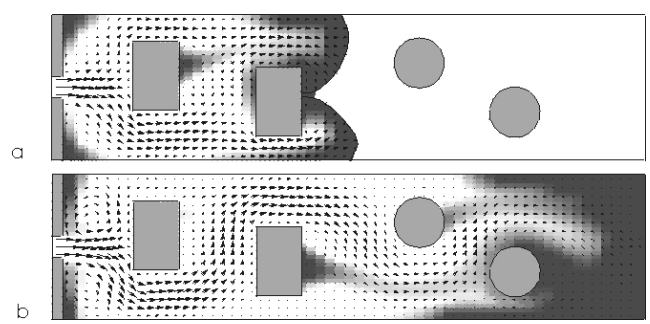

Figure 5. Lost foam casting simulation for the geometry shown in Figure 4. The foam residue and flow patterns are shown at about 50% (*a*) and 100% (*b*) fill fractions.

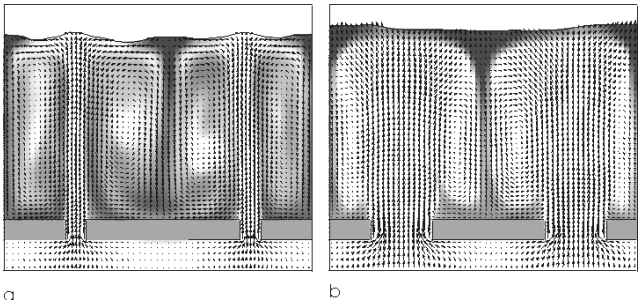

Figure 6. Predicted scalar distribution and flow patterns during low pressure filling process: (*a*) narrow gates, (*b*) wide gates. The scalar variable represents surface oxide film.

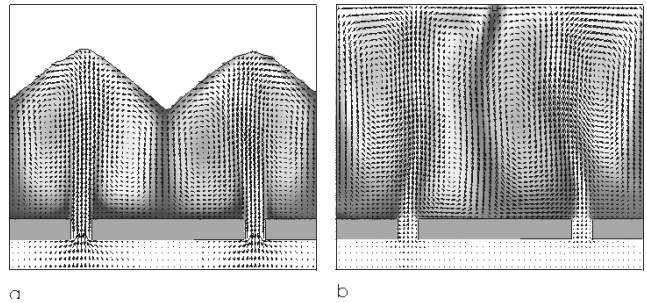

Figure 7. Predicted scalar distribution and flow patterns during lost foam filling process: (*a*) 75% full, (*b*) full mold. The foam material above the metal front is not shown. The scalar variable represents foam residue.

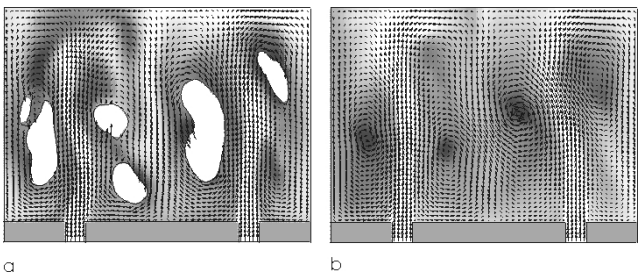

Figure 8. Scalar distribution and flow patterns during high pressure filling process: (*a*) 90% full, (*b*) 100% full cavity. The scalar variable represents oxide film and trapped air.

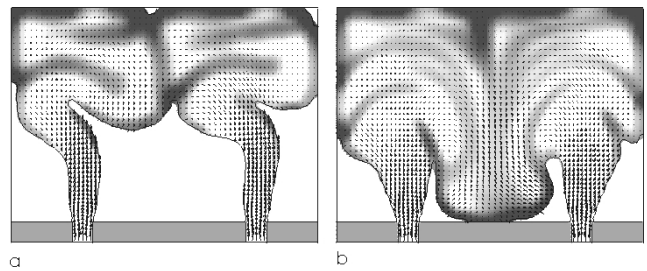

Figure 9. Scalar distribution and flow patterns during semi-solid metal filling process: (*a*) 50% full, (*b*) 90% full mold. The scalar variable represents surface oxide film.

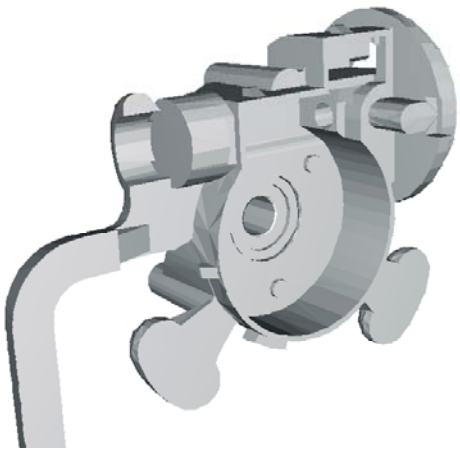

Figure 10. CAD model of the wiper housing component, including a feeding system and overflows.

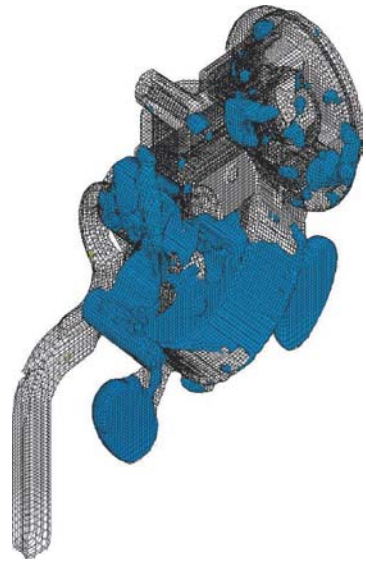

Figure 11. Predicted trapped air bubbles (blue) at about 60% fill fraction during high pressure filling. The pressure in each bubble is computed as a function of its volume.

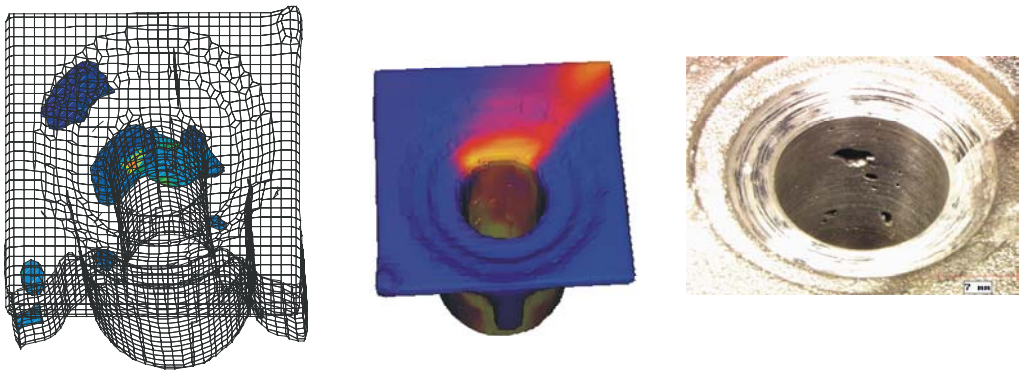

Figure 12. Defect predictions for the wiper housing casting: (*left*) air bubbles trapped in the nearly full cavity, (*middle*) scalar concentration distribution at the end of filling (blue – low, yellow – high) and (*right*) the actual defects on the surface of the casting due to trapped air bubbles.

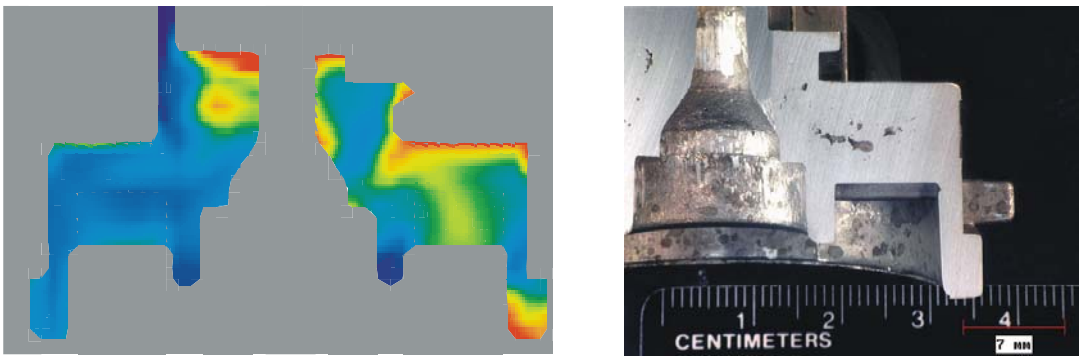

Figure 13. Internal porosity predictions: (*left*) scalar distribution in a cross-section in the casting (blue – low, red – high), (*right*) the actual defects due to trapped air bubble. Predicted high concentration of the scalar near the die surface is less likely to cause structural problems. Those inclusions will either escape through the vents or stay on the surface possibly resulting in poor surface finish.