Predicting Defects in Lost Foam Castings

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Introduction

There is increasing interest in the lost foam casting technique because of its ability to produce near-net-shaped components of high complexity. The idea is to first make a prototype of the part to be cast in foam. This is then used as a pattern that can be placed in a box and surrounded by sand. Finally, metal is poured such that it smoothly replaces the foam by melting and/or evaporating it.

The stiffness of the foam makes it possible to cast parts having thin walls or other fine-scale features, and since the foam does not have to be removed at the end of the casting process, parts can be made that require fewer gaskets to assemble. Furthermore, because the foam pattern holds the sand (mold) in place there is little need to use binders in the sand, which means that the sand doesn't have to be disposed of and can be used again. All these features make the lost foam process highly attractive to manufacturers.

Unfortunately, one rarely gets a free lunch and lost foam casting is no exception. For the process to be successful there must be a high degree of process control. Foams must have the proper characteristics and be coated with just the right material, and pouring sprues and gates for delivering metal to the mold must be carefully arranged. Metal pour temperatures must be sufficiently high to prevent premature solidification. And finally, the filling pattern of a mold should be such that metal fronts do not merge in a way that traps liquefied foam material, which could cause internal defects in the cast part.

To help casters address some of these difficult problems the computational fluid dynamics (CFD) program ***FLOW-3DÒ*** has been outfitted with special modeling capabilities to simulate the lost foam process. Using these models, it is possible to simulate the filling of a lost foam mold and the subsequent solidification of the metal. An extra feature in ***FLOW-3DÒ*** is the capability to predict where folds or other defects associated with trapped foam products are likely to be located.

The purpose of this paper is to demonstrate the usefulness and accuracy of lost foam predictions made with ***FLOW-3DÒ*** by presenting a direct comparison between experimental and computational results. The example chosen for this comparison is described in the next section. Subsequent sections present the comparisons with an emphasis on how the computational results can be used to understand why things happened as they did. This last point is most important, because it offers the user direct evidence and insight into how a casting could be improved.

Test Example

The part to be cast, called the "box cast," was designed by the General Motors Corporation as a test part for research into the lost foam casting process. Although basically simple, the part has posts, partitions, and sections of differing thickness, all things known to be a challenge to casters. In the present case, the part was gated in a non-optimum way. This was done in order to increase the likelihood of defects that could serve as a guideline for comparing the relative advantages of a variety of process changes. Figure 1 shows the part with an attached sprue 19.5 inches (49.53cm) high at one end. The box part is resting horizontally with its internal posts and partitions upward.

The single gate between the sprue and the box is a circular cylinder about 2.0cm in diameter.

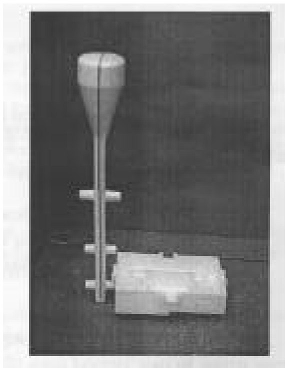

Figure 1. Picture of box part with sprue attached at one side.

Two additional gates are visible along the sprue, which were used to fill the part when the box was oriented vertically rather than horizontally.

As will be seen, an important feature is the variable thickness of the box bottom. Half the bottom nearest the gate is about twice as thick (1.98cm) as the remainder of the bottom (1.03cm).

Aluminum 356 was poured into the room temperature mold at 1540°F (838°C). Experiments indicated that the average speed at which metal moved into the foam was approximately 2.1 in/s (5.334 cm/s).

The particular experiments that we shall be comparing with were done by Dr. Jason Hopper under the auspices of the AFS-DoE-LFC Foam Casting Consortium managed by the University of Alabama, Birmingham. The cooperation of the Consortium, as well as that of General Motors, in making available these data is greatly appreciated.

<u>Numerical Model</u>

For simplicity in our numerical model we have removed the sprue and replaced its presence at the entrance to the gate with a boundary condition consisting of liquid metal at 1540°F (838°C) and having a driving pressure corresponding to a metalostatic head of 19.5 inches (49.53cm).

The computational grid chosen to represent the box pattern consisted of 124,200 rectangular elements in a regular array of 23 by 60 by 90 elements. A stereolithography file was used to specify the box geometry. ***FLOW-3D***$^{\text{Ò}}$ automatically converted this data file into a discrete computational model using its **FAVOR**$^{\text{tm}}$ advantage.

<u>Computational Results</u>

General

All computations indicated a smooth filling history with the metal flowing continuously from the gate toward the opposite end of the box. Figure 2 is a snapshot of the flow computed in the bottom of the box after 1.6s of filling. A characteristic feature of this flow that should be noted is that metal enters the box as a rather narrow jet, while at the metal-foam interface it is moving tangential to the interface toward the sides of the box. This flow carries degraded foam material that could be trapped and cause internal defects.

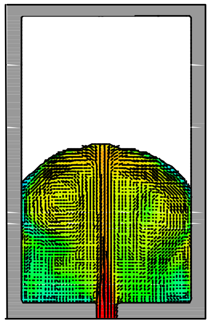

Figure 2. Snapshot of flow in bottom surface of box at t= 1.8s after start of filling. Note in particular the narrow jet and fountain-like flow at the interface.

A general idea of the overall filling history is given in Fig.3, where color indicates the time of filling (red=last, blue=first). It can be seen that the first place to fill is at the in-gate (i.e., bluest region) while the last place to fill (i.e., most red region) is at the top-right corner, the furthest point from the in-gate.

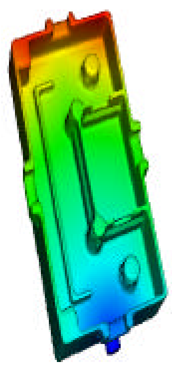

Figure 3. Color indicates time of filling (blue is earliest and red latest). Gate is at bottom.

Bottom Defects

Defects observed in the experiments were primarily confined to surface observations. For example, Dr. Hopper noted that on the bottom of the box fold defects were consistently observed on that portion having a thinner thickness. Furthermore, these defects were quite repeatable. A felt tip pen was used to mark these defect locations shown in Fig.4 (left).

For comparison, Fig.4 (middle) shows the computed probability of defects in the bottom-most layer of computational elements, while Fig.4 (right) shows the same thing in the second layer of elements above the bottom of the box.

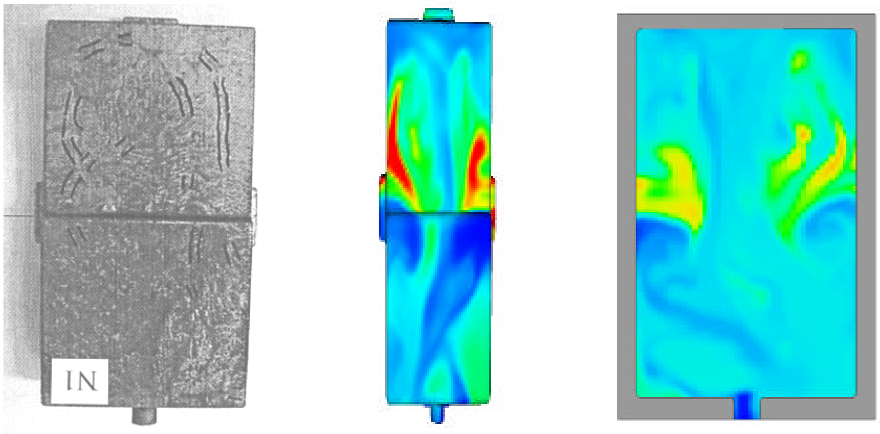

Figure 4. Experimentally observed defects (left) compared with computational predictions in bottom (middle) and slightly deeper into bottom surface (right). Red indicates highest probability for defects.

Clearly, the computation has identified the thinner bottom section as having a much greater likelihood of defects. Even more impressive is the fact that the computation, in agreement with the data, has predicted that defects are most likely to lie toward the left and right sides of the bottom surface. Fig.4 (right) further shows the tendency of defects on the right side of the bottom to lie in two parallel bands.

Top Defects

On the top surface of the box a variety of defects were found to occur. For example, Fig. 5 indicates that a cold shut and "blister" were typically seen on the top of a short partition located closest to the last place to fill (top left corner in the figure). A close-up of these defects, together with another cold shut seen on the top of the post located to the immediate left of the other cold shuts, is shown in Fig.6.

All of these defects were predicted by ***FLOW-3D***Ò as can be seen from Fig.7, which shows the high probability of defects on the post and along the top of the partition that are located nearest the last place to fill.

Origin of Defects

The agreement between experiment and computation is remarkable, but the true power of simulation is that it not only indicates problem areas, it also gives detailed information as

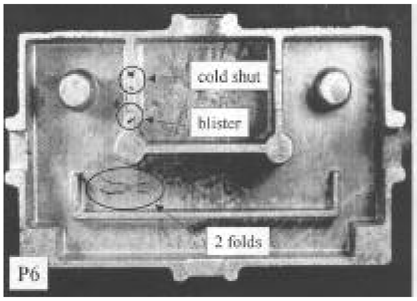

Figure 5. Defects observed on top surface of box.

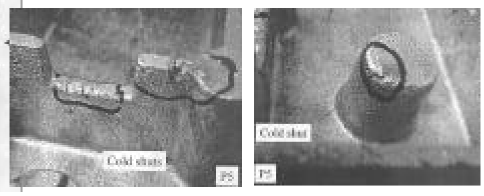

Figure 6. Close up of cold-shut defects on partition and post.

to why the problems have occurred. For example, if we look at the metal temperature in the mold, Fig.8, a short time after filling (t=6.0s) we can see that the coldest spot is precisely where Dr. Hopper observed cold shuts in the partition.

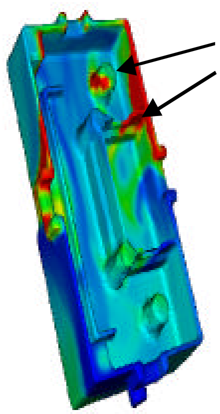

Figure 7. Predicted location of defects (red). Cold shuts observed in Fig. 6 are indicated by arrows.

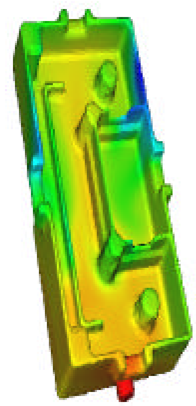

Figure 8. Temperature at end of computation (t=6.0s).

It is even more interesting to learn why the coldest spot is not at the last place to fill where it might be expected. Residual momentum in the metal at the end of filling carries cold metal from the last place to fill back to the partition where the observed “cold shuts” (see Figs.5-6) occurred.

Returning to the defects on the bottom surface, a review of the computational results shows that these tend to be located toward the side-walls because of the flow pattern that develops during filling. As observed earlier, there is a tangential flow of metal along the metal-foam interface that is directed toward the sides of flat sections of the part. At the sides of the bottom, two such sections meet at right angles, so one would expect an accumulation of foam residue along these corners. However, excess fluid momentum at the end of filling is strongest in the sidewalls, which eventually pushes the surface defect material away from the corners and a little way back into the bottom surface.

Excess and Residual Momentum Effects

It has already been pointed out that residual momentum is responsible for moving the coldest metal away from the last place to fill, and for altering the location of trapped foam residue. For this reason it is worthwhile to consider the origin of residual momentum and what might be done about it.

Metal enters the mold through the 2cm-diameter gate. Since the speed of advance of the metal-foam interface is nearly constant, the volume flow of metal through the gate must be proportional to the area of the interface (assuming the pressure head in the sprue is sufficient to maintain the flow). This area increases rapidly as the interface expands outward to fill the box pattern, Fig. 9. Inspection of the computed metal velocity in the gate reveals that it reaches a maximum speed of about 207cm/s even though the interface speed is only 5.33cm/s.

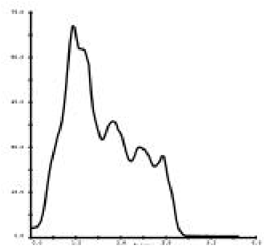

Figure 9. Metal front area versus time. Gate velocity is proportional to this area.

A significant consequence of such high-speed metal entering the mold is the potential for turbulent mixing of foam residue into the body of the metal. In this instance, for example, metal jets straight into the box cavity from the circular gate. At the metal-foam interface the high-speed jet flow is deflected, causing metal to flow tangentially along the interface and trapping foam residue in the corners of the box.

From a general point of view, the presence of more (excess) momentum in the metal than is needed to simply fill the pattern is a cause for concern. Excess momentum appears in the form of secondary flows, often eddies or reciculations, that may mix liquid and/or solid foam products into the bulk metal. These secondary flows may also cause folding of the interface, which is another way to generate defects by trapped foam material.

A relatively simple way to reduce the amount of residual or excess momentum is to redesign the gate(s) so that there is a larger cross sectional area feeding the pattern. Ideally, the gate(s) should also spread out the metal flow and prevent the formation of localized high-speed flows such as jets.

Testing the Concept of Excess Momentum

A test of this idea was conducted by repeating the simulation using a modified gate. The original cylindrical gate was flared out to increase (approximately double) its surface area where it is attached to the surface of the box, Fig.10. It was hoped that the incoming metal flow would stay

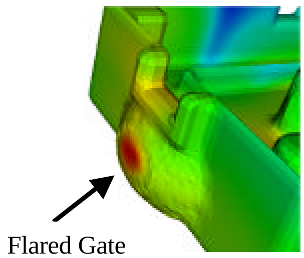

Figure 10. Modified (flared) gate intended to reduce metal velocity in gate.

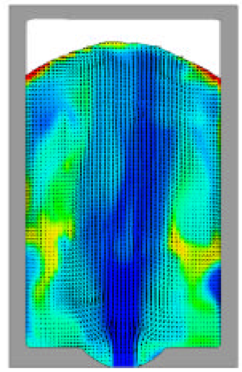

Figure 11. Flow in box bottom using modified gate.

attached to the sides of the gate, but the flare angle was too much and the metal continued to jet into the box. However, the flare did cause a recirculation at the base of the jet that helped it spread out, Fig. 11, reducing its speed considerably.

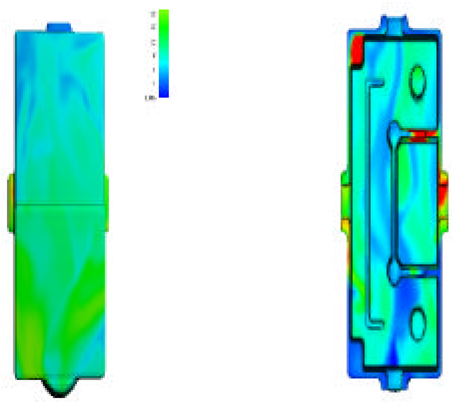

Figure 12. Defect predictions when modified gate is used. Defect probability is much less than with original gate (compare Figs. 4 and 7).

With the new gating, the prediction of defect potential in the bottom and top surfaces, Fig.12, is much less than it was with the original gating (compare with Figs. 4 and 7). At least, computationally, this confirms the assertion that excess momentum arising from poorly sized gates can be a source of casting defects in the lost foam process.

Summary

It has been shown through the comparison of computation results with carefully performed experiments that ***FLOW-3D***Ò does an excellent job of identifying probable defects in lost foam castings.

Furthermore, the computational results provided by ***FLOW-3D***Ò have been shown to give useful insight into the origin of defects, which can then be used as the basis for making improvements in the process. In this application, for example, the computational results suggested that a modification of the gate would significantly reduce the potential for defects. Follow up computations confirmed the usefulness of such a modification.

Only one empirical datum, the average metal-foam interface speed, is needed to employ ***FLOW-3D***Ò for lost foam casting. This approach condenses many process parameters, including coatings, into a single empirical parameter.