LOST FOAM CASTING SIMULATION WITH DEFECT PREDICTION

C.W. Hirt and M.R. Barkhudarov

Flow Science, Inc.
1257 40th Street
Los Alamos, NM 87544

Abstract

The Lost Foam (LF) or Expendable Pattern Casting (EPC) process is gaining recognition as the process of choice for making high core content castings with less machining and assembly. The LF process also reduces the amount of sand and chemicals in molds leading to additional cost and environmental advantages. The principal disadvantage with the LF process is that it is not understood well enough to insure short production lead times. Better tools and more experience are needed to guide users in selecting a variety of process parameters.

A new three-dimensional LF casting model has been developed that can answer many important issues associated with filling and solidification processes. The model uses a heat transfer controlled algorithm for the displacement of foam by metal. The foam is characterized by its density and specific heat plus heats-of-transformation for melting and vaporization processes. Additional model features include spatially variable foam properties, lighteners, premature solidification, thermal mixing caused by residual momentum, and incomplete filling at low metalostatic head pressure.

Coupled with the LF model development is a second new technique for the prediction of defects. This scheme uses a higher order scalar transport equation with a special source term to define the amount of oxide and foam residue at the metal-foam interface entrained into the flow. The distribution of the scalar function gives a probability distribution for inclusions caused by folds, surface turbulence and other flow phenomena. Because the evolution of defect material is governed by a transport equation, this model includes advection and dispersion of defects, both during filling as well as after filling, caused by residual momentum and natural convection effects.

To be presented at the Modeling of Casting, Welding and Advanced Solidification Processes VIII Conference, June 7-12, 1998, Catamaran Hotel, San Diego, California.

Introduction

The Lost Foam or Expendable Pattern Casting uses a polystyrene foam material as an initial pattern for making a sand mold. Metal is then poured into the mold displacing the foam to form the part. Thin sections or relatively small details can be molded in this way because the foam adds support to the sand before it is replaced by metal.

Another advantage offered by a foam core is that it retards the motion of metal during filling. This reduces splashing and air entrapment, which improves the quality of the part. A further advantage is that most of the sand in the mold can be reused because it does not require a binder to stay in place.

In short, the Lost Foam process has many positive features that make it attractive for the production of many types of high volume parts. As with most things in life, however, there is always a price to pay. For example, there is an increased possibility for inclusions by trapped foam residue, an increased potential for cold shuts because of the heat loss to the foam, and filling patterns that defy expectations and make gating design more difficult.

To address some of these problems, a new Lost Foam modeling capability has been developed and incorporated into the commercial casting simulation program FLOW-3D (1). The model also contains an estimate of the distribution of possible inclusions caused by oxides or foam residue. This feature not only captures the initial entrainment of impurities by folds or the meeting of different metal fronts but also predicts the redistribution of those inclusions by subsequent flow processes.

The Lost Foam Model

Lost foam casting differs from other types of casting because foam occupies the mold cavity and offers a resistance to the flow of metal. Momentum, which can dominate the mold filling process in ordinary casting, plays only a small role in the Lost Foam process. To construct a Lost Foam model, we begin with an existing casting modeling program. The program selected uses a finite volume method based on a fixed grid of rectangular control volumes. Arbitrary geometries are defined in the grid using the FAVOR technique, which employs fractional face areas and fractional volumes of grid cells to better match the curved boundaries of a mold. Free metal surfaces are tracked with the Volume-of-Fluid (VOF) method.

Foam is considered to be a special kind of obstacle that can prevent the flow of metal unless it is heated sufficiently to lose its strength. In this sense the movement of metal into foam is controlled by heat transfer mechanisms and not by pressure or inertia of the metal.

When metal enters a grid control volume containing foam, the heat transferred to the foam from the metal during one increment in time is computed. This amount is then used to compute the amount of foam that is decomposed and raised to the temperature of the metal. When computing the amount of foam decomposed, it is necessary to include the heats-of-transformation for melting and vaporization of the foam. Of course, the energy transferred to the foam is removed from the metal.

Metal advances through the action of a sink equal to the amount of foam volume removed in each control volume. The sink is specified in terms of velocity components at the metal surface, which keeps the metal moving into the foam as long as the pressure in the metal is sufficiently high.

Since melting and/or vaporization of foam removes heat from the metal, it can slow down the rate of heat transfer. However, this effect is usually quite small because once the metal reaches its liquidus temperature, it has a large reserve of latent heat that must be removed before the temperature can be lowered further.

No attempt has been made in the model to directly model the flow of gas produced from vaporized foam. The importance of gas is well known in terms of the effect that different coating permeabilities placed on the surface of the foam pattern may have on the performance of a casting. With insufficient permeability, gas buildup may actually blow metal back out the filling sprue. Any model that attempts to model the gas will of necessity be complex, requiring more user-supplied data and consuming considerably more computer resources.

The effects of coating permeability are approximately included in the present model through a change in the metal-to-foam heat-transfer coefficient. The reasoning behind this proposal is that the rate of heat transfer from metal to foam should be proportional to the thickness of the gas region. A low permeability coating would allow gas buildup and reduce heat transfer.

Metal-to-Foam Heat Transfer

The foam model involves mostly known or easily estimated physical properties. These properties include foam density, specific heat, heats-of-transformation for melting and vaporization and the corresponding temperatures of melting and vaporization. An additional parameter required by the model is the metal-to-foam heat-transfer rate. This parameter must be determined from experimental data.

Simple tests involving the time for metal to penetrate a vertical column of foam should be sufficient for this purpose. An analysis of the speed at which metal advances into foam in our model is approximated by the ratio between the heat-transfer coefficient and the product of foam density times the foam specific heat. If a filling time is known for some test case, then the heat transfer coefficient can be estimated from this relation.

When using the Lost Foam model, foam is initialized in a simulation as a special type of obstacle, one that can change shape (e.g., vaporize). Different foam properties may be initialized in different regions to account for non-uniform form, or lighteners (i.e., holes) can be cut in the foam defining sprues and runners.

A Test Example -- Casting A Horizontal Plate

A simple illustration of the new model is the casting of a horizontal plate as reported by Yao and Shivkumar (2). In their tests a 15 cm by 20 cm plate, 1.3 cm thick, was cast using several different materials. Here we consider Aluminum poured at 1023 K with a 28 cm high sprue. The properties used for the Aluminum (left column) and foam (right column) in CGS units, with temperatures in degrees K, were:

Density = 2.7	Density = 0.02
Specific Heat = 8.37E+6	Density * Specific Heat = 8.0E+5
Conductivity = 1.88E+7	Density * Melt Energy = 1.6E+5
Thermal Expansion = 3.0E-5	Density * Vaporization Energy = 0.8E+5
Liquidus Temperature = 933.0	Melt Temperature = 373.0
Solidus Temperature = 933.0	Vaporization Temperature =750.0.
Latent Heat of Fusion = 3.94E+9	
Pour (gate) Temperature = 988.2	

Observations showed the plate was nearly filled in about 2.0 s. From this we estimated the metal-to-foam heat transfer coefficient to be about 6.0E+6 gm/s^3/K. Figure 1 contains the observed filling configuration at a series of times (0.6, 1.0, 1.8 and 2.5 s). Filling in the

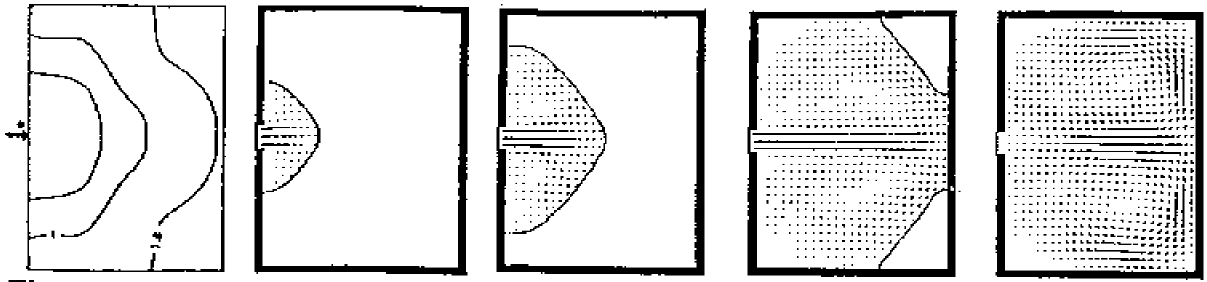

Figure 1. - Horizontal plate results at times 0.6, 1.0, 1.8 and 2.5 s. Experimental data from Ref. 2 at left.

simulation is completed by 2.0 s. When compared to the computed configurations, we see remarkably good correspondence in metal front shapes.

The calculations show some small differences with data in the time to reach each contour. In fact, the calculations exhibit a nearly uniform filling, while experiments seem to indicate an unsteady filling as evidenced by the non-uniform spacing of the interface contours along the horizontal mid-line. Since no information about the reproducibility of the experiment was given, it is unknown if these variations are real or the result of experimental conditions, e.g., a non-uniform pouring of the metal.

Aside from qualitative agreement with the test data, the computed results exhibit some interesting features associated with Lost Foam casting. For one thing, the metal front temperature reaches the liquidus temperature very quickly and then remains there for most of the filling time. Another observation is the smooth filling pattern, which is very different from what would be observed if the foam was not there. After the plate has completely filled there remains a substantial circulation that reduces the spread between the minimum and maximum temperatures observed in the metal (last frame in Fig.1). Residual momentum of this magnitude will modify the solidification history of the part.

Mushy Zone Considerations

As previously noted, molten metal must transfer heat to the foam in order to displace it. This causes the metal at the front to fall fairly quickly to its liquidus temperature. As more heat is removed, the solid fraction at the front begins to increase. Because the heat of transformation of most metals is relatively high compared to the heat required to degrade foam, the solid fraction increases slowly.

An increase in solid fraction has at least two important consequences. One occurs when two fronts come together, for instance, behind an obstruction in the flow. When the solid fraction is high, the surfaces can no longer knit smoothly together.

A second difficulty is that the viscosity of the metal increases with increasing solid fraction. Experiments reveal (3) that in material such as 319 Aluminum, the viscosity begins a significant increase in magnitude when the solid fraction exceeds about 12% (the point of coherency). Beyond a solid fraction of about 50% (the point of rigidity) the viscosity begins an extremely rapid increase, and the material behaves almost like a solid.

To illustrate how our model can be used to investigate possible solidification problems at the metal front, consider the situation that arises in a long, vertical sprue containing several horizontal notches (e.g., runners), Figure 2. The sprue is circular with a diameter of 5.08 cm, and each of the notches is a circular disk, 2 cm thick with a diameter of 10 cm. In one case there are four notches, while in the second there is only one near the bottom of the sprue.

Calculational results using Aluminum for the metal are shown in Figure 2 at the time that metal is near the entrance to the bottom notch. The shaded region in each plot is the region at the metal front where the solid fraction exceeds 12%. The peak solid fraction along the axis of the sprue is about 0.13 in the four notch case, but 0.25, or twice as much, when only one notch is present. The thickness of the front in which the solid fraction exceeds the coherency level is also about twice as large in the case without notches.

Clearly, the presence or absence of the extra notches is having a significant effect on the metal front that reaches the bottom of the sprue. Without notches the solid fraction is already well beyond the point of coherency, which indicates that filling from the bottom of the sprue may be difficult, and that laps and folds occurring in metal fed from this region may not knit well enough to make a sound part.

Because the simulations give us a complete picture of the entire filling process, it is easy to see how the multiple notches affect the flow. By the time metal reaches the entrance to a notch it has already developed a mushy zone. Metal is able to move into the notch as fast as it continues down the sprue because the metalostatic head is more than enough to overshadow what little axial momentum there is. Consequently, the notch draws off a good portion of the mushy material at the front, which is then replaced by hot metal following along behind the front continuing down the sprue.

When the notches are absent, there is a continuous buildup of solid fraction at the metal front. Given a long enough sprue, it is obvious that solidification difficulties must eventually develop. However, when notches or side pockets are placed along the sprue to remove the solid accumulated at the front, it makes it possible to have long sprues and runners.

Not only is the mushy zone reduced by the presence of side pockets, but any contamination, such as sand or foam residue, that may have been accumulated at the front will also be reduced by the same mechanism. This topic is discussed next.

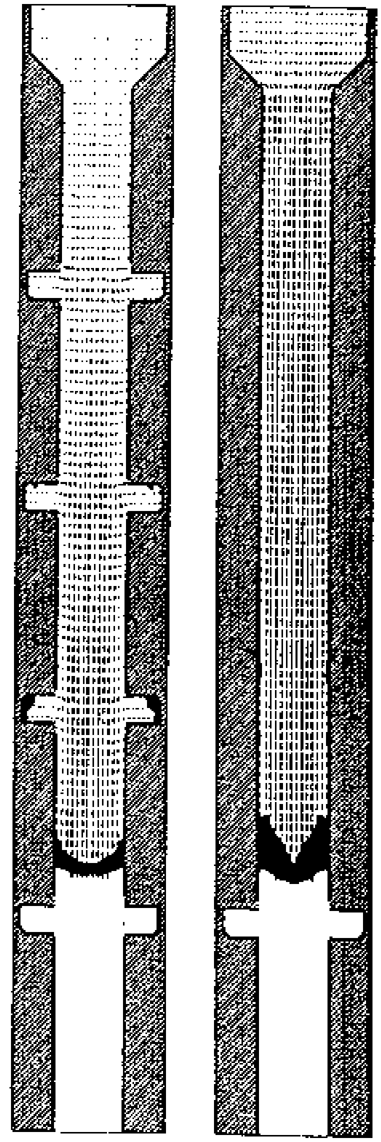

Figure 2 – Effect of notches on solid fraction at front of metal filling a sprue.

Tracking Defects

Most defects observed in Lost Foam cast parts arise 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 residue from degraded and vaporized polystyrene. Entrainment arises from the meeting of two fronts (folds or laps): material remaining on the surface of a part (wrinkles) and foam material surrounded and trapped by metal due to surface turbulence at the front (bubbles).

Once residue is trapped, it continues to move with the flowing metal and may be diluted and dispersed if the flow exhibits enough shear (possibly turbulence).

To model surface generated defects, a scalar transport model has been coupled with the Lost Foam casting model. The idea is that degraded foam can leave a carbon residue on the advancing metal surface. This residue is represented by a scalar variable that is initially zero. As foam is melted or vaporized in a control volume, the scalar quantity in that volume is incremented by an amount proportional to the mass of degraded foam. If the amount of residue were known it would determine the coefficient of proportionality. But even when the exact amount is unknown, we can still interpret the scalar as proportional to the amount of defect material, hence to the probability of a defect. This scalar is then allowed to advect with the metal using a second order, monotonicity-preserving scheme for increased accuracy.

At the conclusion of a simulation, the distribution of the scalar indicates locations where residue is likely to be. With proper gating, most of the scalar tracked residue is typically found at the last place to fill, as would be expected. In other words, residue accumulates at the front and is pushed along until there is nowhere else for it to go.

Most interesting are the situations where two fronts meet, trapping surface residue in the interior of the metal or near corners where flow recirculation regions may develop. Finally, we note that recirculating flow remaining in metal after a mold has filled can redistribute surface-generated contaminants to regions in a cast part far from where they originated.

Illustration of Defect Prediction in Lightener Example

To illustrate the defect tracking model, we shall consider a simple example involving a lightener channel. The lightener is a central hole in foam, usually in a sprue and/or runner, which allows rapid filling of these parts by metal. In this case we consider a vertical cylinder of foam, 25 cm high, with a concentric cylindrical hole. The inner and outer radii of the foam are 1.25 cm and 2.54 cm, respectively. Metal enters the cylinder from the bottom with a hydrostatic pressure head of 28 cm of metal, a value sufficient to fill the entire cylinder. All physical properties for this problem are the same as for the plate example.

Figure 3 shows the progression of the filling, first in the central hole and then filling out to the sides as the foam is evaporated. After filling there remains a pronounced residual circulation in the mold.

At early times the metal appears not to be penetrating the foam near the ingate as fast as it is further up the column. This is a consequence of low pressures in the recirculating regions on either side of the incoming jet of metal. For a short time the pressure in these regions is below atmospheric pressure, which is insufficient to advance the metal front into the foam.

When the scalar defect model is coupled with this example, we find that all scalar material is at first pushed to the outside walls of the cylinder because this is the direction in which the foam is degraded. Dark shading in Figure 3 indicates regions with scalar values greater than a nominal average value. However, if this material does not leave the mold cavity through the coating (a process not modeled), then the residual recirculation existing after filling will carry some of it into the central region of the cylinder, near the inlet, even though in the beginning this region contained no foam (Figure 3, last frame).

Summary Comments

A new Lost Foam modeling capability has been incorporated into the FLOW-3D simulation program. The model has provisions for spatially non-uniform foam densities (or other properties) and also includes lighteners, early solidification, and the prediction of incomplete filling when the applied metalostatic head is insufficient to fill the mold.

A companion development has also been described for the prediction of defect distributions using a scalar concentration function. Defects in this model are assumed to arise at the metal front in proportion to the amount of foam consumed. Defect material is then tracked with the flow so that an accurate accounting can be made of where it is likely to end up.

The Lost Foam model is relatively simple and contains only one unknown parameter, the heat-transfer coefficient between metal and foam, whose value must be determined from experimental tests.

The model does not address some features, such as the gas generated by degraded foam and its interaction with foam coatings. On the other hand, its use in automotive applications is already providing useful insight into gating designs, filling processes and the likelihood and location of potential internal defects.

References

1. R.P. Harper, C.W. Hirt, and J.M. Sicilian, "FLOW-3D: Computational Modeling Power for Scientists and Engineers" (Flow Science, Inc. report FSI-87-00-1, 1987; see also www.flow3d.com).
2. X. Yao and S. Shivkumar, "Mold Filling and Solidification in The Lost Foam Process" (Paper presented at the 99th Casting Congress, Kansas City, MO, 23 April 1995), AFS 95-116.
3. Lars Arnberg, Lennart Backerud, and Guocai Chai, Solidification Characteristics of Aluminum Alloys (American Foundrymen's Society, Inc., Des Plaines, IL 1996) Vol. Dendrite Coherency.

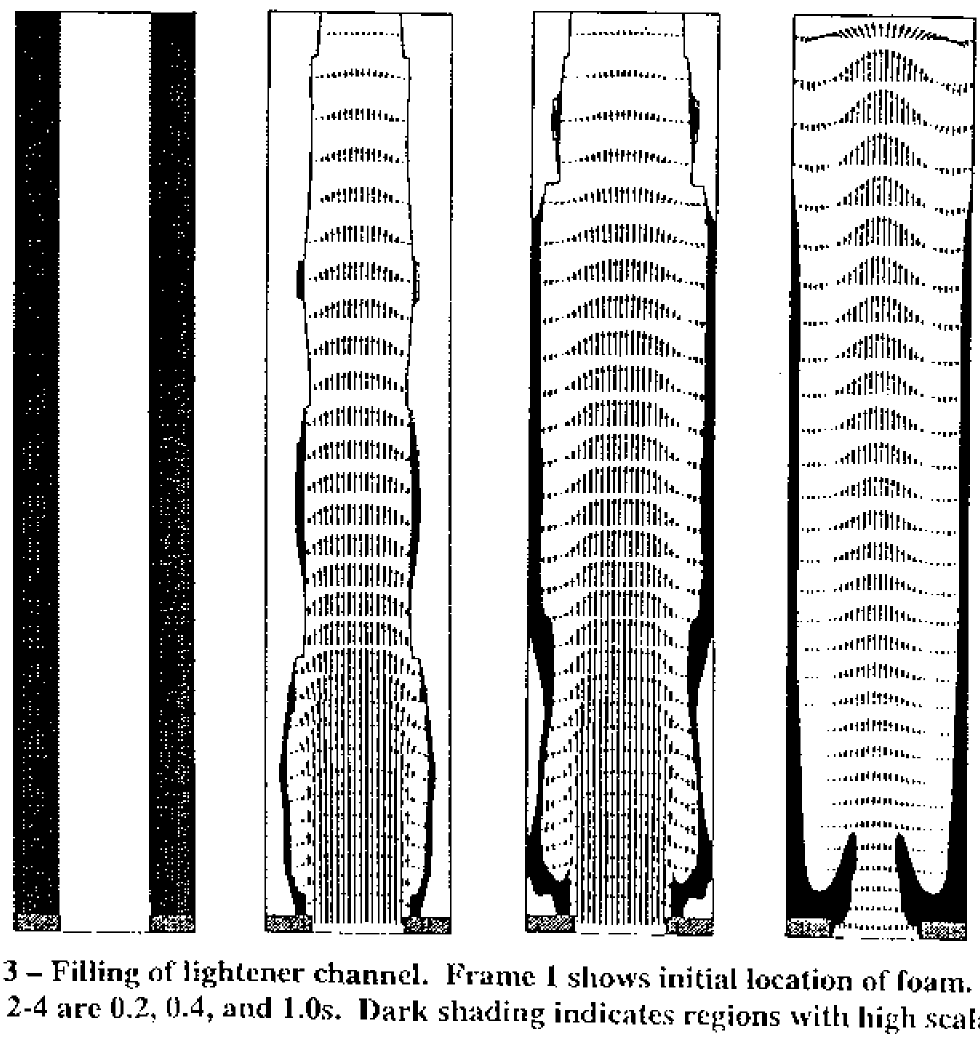

Figure 3 – Filling of lightener channel. Frame 1 shows initial location of foam. Times of frames 2-4 are 0.2, 0.4, and 1.0s. Dark shading indicates regions with high scalar values.