Porosity Simulation for High Pressure Die Castings

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Introduction

Porosity presents major challenges for many die castings. The challenges of porosity become more pronounced as die castings get used in more structural applications. Most of the 2008 International Die Casting Design Competition winners were structural components, and that indicates an increased use of die castings for structural support. This trend is being driven by a desire for lightweight and fuel-efficient designs. Strength and fracture toughness are critical mechanical properties in these structural applications. Porosity can drastically reduce these mechanical properties. Without proper control of porosity, the die casting process can be rejected as an acceptable manufacturing process. This will result in loss of current business as well as possible future business.

In practice, porosity is controlled by first identifying the type of porosity. This determination is used to differentiate between pores resulting from the filling process and pores forming due to the solidification process. With the exception of porosity from dissolved hydrogen, gas porosity is the name given to porosity resulting from filling. A wealth of simulation software packages exist that predict likely locations of this gas porosity. Many of these packages include a calculator to select the correct slow-shot and fast-shot speeds. Once these are selected, a full computational solution of the three dimensional filling pattern is calculated. These types of simulations can help identify areas where air will be entrained, but they cannot indicate the location of porosity due to solidification shrinkage or dissolved hydrogen gas. These types of porosity can form even in areas where little or no air is entrained. If the solidification-related porosity forms at large liquid fractions, the porosity will appear smooth. This can cause the misdiagnosis of the type of porosity. The result is that the wrong solutions are used to treat solidification-related porosity. Solidification simulations coupled with porosity formation models will help avoid the misdiagnosis of the source of porosity. However, the current solidification models are limited in their ability to predict porosity from shrinkage. Miller provided further discussion of these limitations in the February, 2009, issue of LINKS[1].

Niyama

Currently, the Niyama criterion is the most widely utilized to identify areas where shrinkage porosity may occur. This result can be useful in resolving porosity issues, but there are severe limitations to its abilities. The main reason Niyama is limited is because it does not simulate what is physically occurring during solidification. Instead, Niyama is a criteria function which is expressed simply as the ratio of the local temperature gradient and the square root of the cooling rate. Small values of the Niyama criteria indicate an increased tendency for porosity formation. Therefore, Niyama will predict porosity in areas that experience small temperature gradients and large cooling rates. Since Niyama is only a criterion, it does not output porosity fraction or pore diameter. This makes it difficult to understand whether the porosity will be unacceptably large in an area. All Niyama can indicate is whether one area of a casting will have relatively more or less porosity than another area of that same casting.

Porosity Model

To take into consideration other physical parameters such as feeding flow and intensification pressure, complex computer models are needed. Such a model has been developed at the University of Iowa to predict porosity due to solidification shrinkage and dissolved hydrogen gas[2]. This model is based on the solution of a fundamental set of equations that account for many of the important physical phenomena found in solidification. This model, originally developed for gravity casting, has been applied to the high pressure die casting process. It will be available in the next major release of MAGMAsoft[3].

Two major governing equations are needed to calculate the final porosity. The first equation is continuity, a complicated differential equation. However, it is simply an equation that balances the shrinkage with incoming feeding flow and porosity formation. Figure 1 shows a schematic of a control volume. Note that solid, liquid and porosity all coexist in this control volume. The sum of the solid fraction, liquid fraction and pore fraction must equal one. It is assumed in this model that the solid and porosity never deform or move. This means that all shrinkage must be accounted for by inflowing liquid or porosity. To determine when the liquid feeding is cut off and porosity forms, another fundamental governing equation is needed.

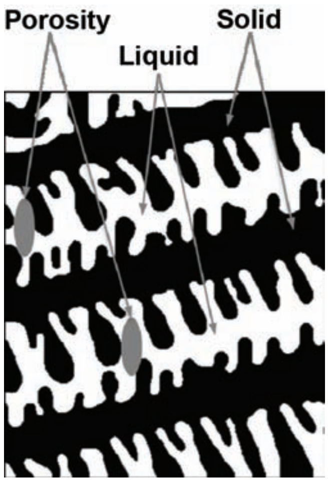

Figure 1 – Schematic of simulation control volume showing solid, liquid and porosity.

The second equation is the momentum equation, and it is used to predict the liquid velocities. Feeding flow is resisted by the liquid viscosity as well as the solid dendritic network permeability. The momentum equation was carefully formulated to be valid from 100% liquid until 100% solid. At low solid fractions, the dendritic network does not exist, and the only resistance

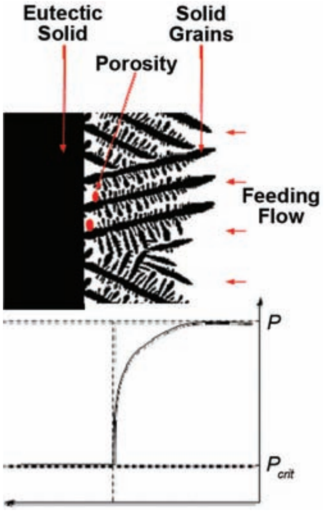

Figure 2 – Schematic showing the melt pressure drop and porosity formation.

to flow is the liquid viscosity. At high solid fractions, the liquid flow is cut off by the dendritic network. Once this flow is cutoff, porosity will start to form and grow.

The time at which liquid feeding is cut off and porosity forms is determined by solving the continuity and momentum equations. Solving these two equations gives the local melt pressure everywhere in the solidifying metal. Once the local pressure drops below a critical value, porosity will nucleate and begin to grow. Figure 2 shows the feeding flow and the associated pressure drop due to the solidifying metal. Liquid is still present in the region below the critical pressure. The remaining shrinkage in this area will result in porosity. The critical pressure is calculated based on the hydrogen gas pressure minus the capillary pressure.

Simulation and Discussion

A simple die casting was simulated to test the capabilities of the new model. This casting was originally produced at The Ohio State University of A380 aluminum alloy. The casting is a small plate with four ribs proceeding vertically from the plate. Throughout the casting, the thickness is roughly 5 mm. The single ingate feeds the casting from one end of the plate. Figure 3 shows the full shot. The casting material properties used for the model were those of A380.

Simulations were conducted to match the casting conditions as close as possible. Only two new aspects of the simulation setup were set to use this new model. The first is the critical capillary pressure. It turns out that the critical capillary pressure is relatively unimportant. If the most accurate simulation possible is desired, this parameter can be set by specifying the surface tension, minimum pore radius and the amount of dissolved hydrogen. For this initial evaluation, it was assumed that no hydrogen was dissolved in the melt. Current work is investigating the effects of including hydrogen in the simulations.

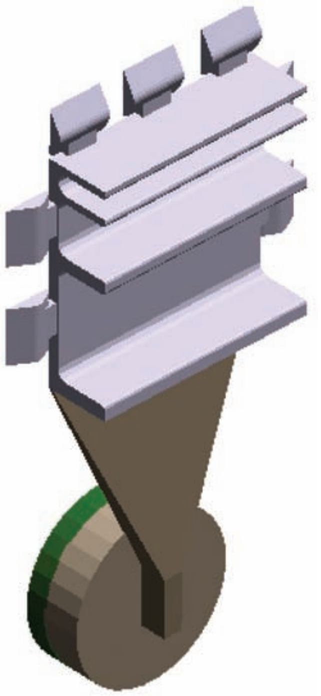

Figure 3 – Solid model of the simulated shot.

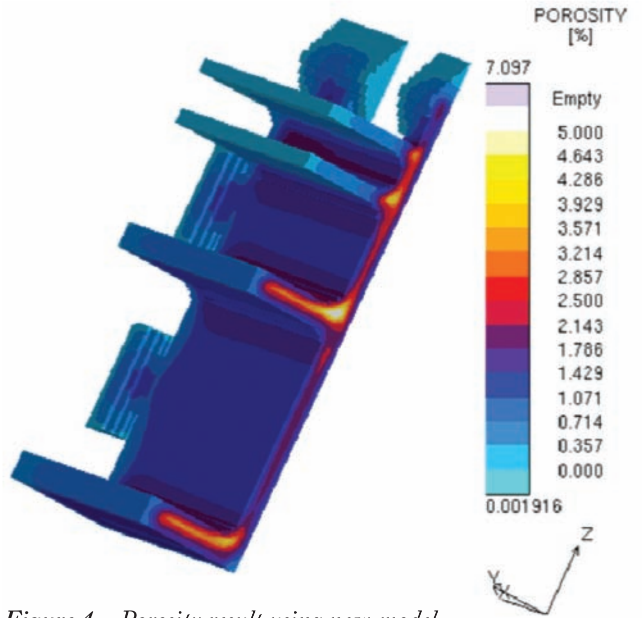

Figure 4 – Porosity result using new model.

The second new input that must be defined is the permeability. This input varies with liquid fraction and is related to the secondary dendrite arm spacing. The arm spacing is also a variable that is dependent on the cooling rate. Although this parameter can have large effects on the final porosity field, the default values for aluminum should yield good results. All other parameters for the simulation are the same as any normal simulation. In Figure 4, the final porosity result is shown.

Three actual castings were sectioned and scanned with a high resolution x-ray computer tomography (XCT) scanner. (The castings were of A380 and provided by The Ohio State University). These scans were completed at the Iowa State University Center for Non-Destructive Evaluation. Roughly 20 Giga-Bytes of digital storage was required for each casting. A filter was developed at the University of Iowa which allowed for the detection of porosity with sub-voxel resolution. This was accomplished by assigning a pore fraction to every voxel in the XCT data. The accuracy of the filter was confirmed using metallographic measurements. From this filtered data, the average pore fraction was calculated for each

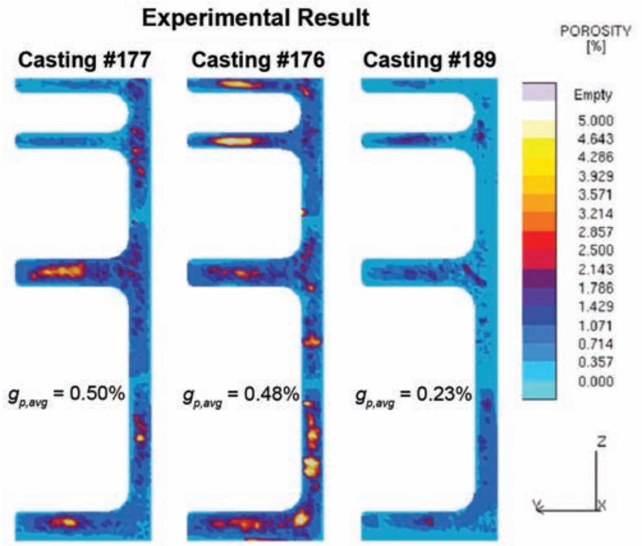

Figure 5 – Experimental measurements averaged across the width of the casting.

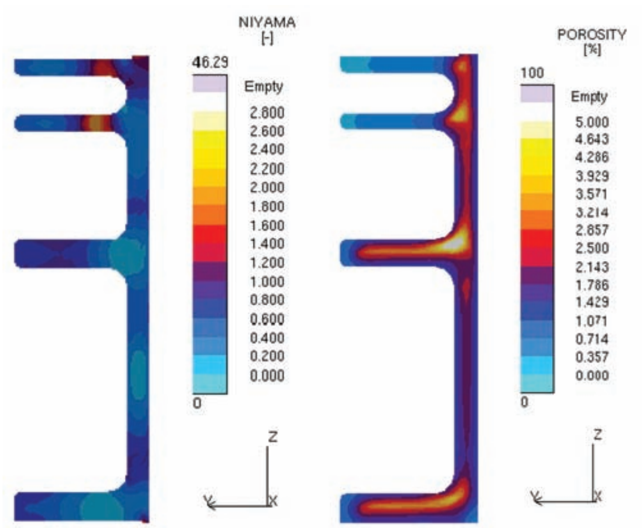

Figure 6 – Comparison of Niyama and University of Iowa model.

casting. The average pore fractions were 0.50, 0.48 and 0.23%. By averaging the porosity across the width of the casting, a two-dimensional pore fraction result was produced from the XCT data. The results of this averaging are shown in Figure 5. Note that there is a fair amount of variation between the three castings, indicating the need for a larger experimental sample.

After averaging the simulated porosity across the width, it is found that prediction (Figure 6) compares well with the experimental data. However, the model does not perfectly match the data. Although the distribution of porosity looks the same for the new model and the experimental results, the total amount of porosity is not correct. In the simulation data, the average pore fraction for the entire plate is 1.72%. This pore fraction is 3 to 9 times larger than the measured average pore fractions. This result is shocking to the average die caster. The implication of this result is that all porosity measured can be accounted for by solidification shrinkage alone. However, the simulation is not completely accurate because it over-predicts the porosity level.

A number of reasons exist for why this new model predicts a larger average pore fraction. The likely most important reason is that solid deformation and motion is not accounted for. With such high applied pressure delivered by the die casting process, it is reasonable to assume that solid in the ingate will deform and move. Other reasons include the possibility of macro-segregation, incorrect simulation parameters, and poor permeability relations. More work is needed to accurately model the ingate and predict the correct average pore fraction.

For comparison, the Niyama result is also shown in Figure 6. When reading a Niyama result, smaller values (blue) correspond to larger levels of porosity. Clearly, one can expect more porosity to form in areas underneath the large ribs. However, near the two smaller ribs, the result is not as straight-forward. This illustrates how Niyama can be difficult to understand when attempting to predict porosity. Also, Niyama does not show any of the asymmetries seen in both the experimental results and the new model results. This is because Niyama is based solely on the temperature evolution of the casting and does not consider the effect of gravity or fluid flow.

Conclusions

The new model for the prediction of porosity in high pressure die castings yields fair agreement with experimental measurements. Volumetric shrinkage alone can account for all of the porosity found inside a die cast component. Die casting gates and runners should always be designed considering shrinkage as an important source of porosity in relatively thick sections. This model, when compared to the Niyama criterion, provides the best agreement with experimental data.

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