Reply

Authors' Reply to Discussion of "Prediction of Shrinkage Pore Volume Fraction Using a Dimensionless Niyama Criterion"

K.D. CARLSON and C. BECKERMANN

DOI: 10.1007/s11661-009-0055-3

Sigworth raises a number of important and interesting questions regarding the Niyama criterion. His Discussion implies that the results of our recent study[1] are not valid. We do not agree with his assertions. In the following, we address each of the questions he raises separately.

His first question concerns the physical significance of the Niyama criterion. Sigworth claims that the formation of shrinkage porosity is *not* governed by the pressure drop associated with the flow of the liquid through the (semisolid) mushy region in a casting. He asserts that his ''detailed'' and ''exact'' calculations, as plotted in Figure 2 in the Discussion, reveal that this pressure drop is too small for shrinkage porosity to form.

The calculations in our article[1] show the exact opposite: the pressure drop can indeed be sufficient for shrinkage porosity to form. The calculations of Sigworth and of Reference 1 are both based on Darcy's law. The differences in the two calculations lie in the relation used for the permeability of the mush. We used the Kozeny–Carman relation together with the secondary dendrite arm spacing,[1] whereas Sigworth used the more simple Hagen–Poiseuille relation together with primary dendrite arm spacing. These two permeability expressions give very different values for the pressure drop, especially at low liquid fractions. These differences are sufficient to explain the different conclusions reached by Sigworth and ourselves. Of course, one could claim that the Hagen–Poiseuille relation for the permeability is more accurate than the Kozeny–Carman relation, but such a claim ignores considerable experimental evidence to the contrary. This evidence is not only available in the porous media literature, but it is also presented directly in our article.[1]

One outcome of our pressure drop calculations is the prediction of a critical Niyama value below which shrinkage porosity forms. We show that our predicted critical value is in complete agreement with the critical Niyama value that was determined experimentally by the present authors and co-workers in a previous study involving hundreds of steel castings.[2] How can Sigworth ignore this quantitative experimental validation of our pressure drop calculations? If our pressure drop calculations were inaccurate, a very different and incorrect critical Niyama value would be predicted.

Sigworth offers an alternative explanation for the Niyama criterion that is based on a critical angle for the taper of the liquid pool in the center of a plate casting. This ''geometric'' model appears to completely ignore the presence of a mushy region. How can isolated, purely liquid pockets form along the centerline of a plate casting when feeding is relatively ''easy'' through at least the first 50 pct of the mush? We certainly concur that sufficient taper will prevent shrinkage porosity in a plate casting, but we do not agree that shrinkage porosity can be explained solely based on geometric arguments. This would imply, for example, that the magnitude of the solidification shrinkage (*i.e.*, the relative density difference between the liquid and solid) and applied pressure have no effect on shrinkage porosity formation in a plate casting, which seems hard to believe. We have performed experiments that demonstrated that centerline shrinkage porosity in a steel plate casting can be substantially reduced through the use of riser pressurization.[3]

Sigworth's geometric explanation also implies that the Niyama criterion cannot be used as a *local* thermal criterion to predict the distribution of shrinkage porosity in a casting, but only for a casting section (*i.e.*, a platelike shape) as a whole. This implication ignores strong experimental evidence to the contrary. We show in our article (Figures 1 and 8 in Reference 1), as well as in numerous other studies involving castings of various grades of steel and nickel-based alloys,[2,4,5] that the Niyama criterion can indeed be used as a local thermal criterion, because the Niyama criterion predicts not only the presence or absence of shrinkage porosity in a plate casting as a whole, but also the exact location and distribution of this porosity inside the plates. Furthermore, Figure 8 in Reference 1 shows that the experimentally measured local shrinkage porosity volume fractions are predicted correctly. All regions in a casting with Niyama values below the critical value have shrinkage porosity. We demonstrated this for complex-shaped castings in a recent study of leaking valves.[6] We have even been able to use the Niyama criterion to predict the taper necessary to prevent shrinkage porosity in platelike steel casting sections.[7]

Later in his Discussion, Sigworth actually concedes that, because of the narrow freezing range of steel, the Niyama criterion can be used as a local thermal criterion to predict shrinkage porosity in steel castings. However, in his second question, he raises the issue of whether the Niyama criterion can be used for other alloy systems, which have different thermal and solidification characteristics. Sigworth states that the Niyama criterion should not be used for alloys with a long freezing range, such as common aluminum, copper, and magnesium

K.D. CARLSON, Research Engineer, and C. BECKERMANN, Professor, are with the Department of Mechanical and Industrial Engineering, University of Iowa, Iowa City, IA 52242. Contact e-mail: becker@engineering.uiowa.edu
Reply submitted August 19, 2009.
Article published online October 17, 2009

casting alloys. In sand casting of such alloys, the mushy region can extend over very long distances; thus, he asserts that a local thermal criterion is not appropriate.

We believe that the modified (not the original) Niyama criterion presented in our study, in principle,[1] can be used for long freezing range alloys, although we do not have direct experimental validation. Our modified Niyama criterion takes into account the exact solidification characteristics of an alloy, including the amount of eutectic that may form. The different thermal characteristics are automatically taken into account when performing the casting simulation in which the Niyama criterion is calculated. Assuming there is an open feed path to the riser (otherwise, the Niyama criterion would not be applicable), the shrinkage porosity predicted by the Niyama criterion usually forms in the mushy region at high solid fractions. At lower solid fractions, the pressure drop is indeed negligibly small. Therefore, in a casting simulation, the Niyama criterion is always evaluated at a temperature near the end of the solidification interval. Because of this, it is still useful as a local thermal criterion in long freezing range alloys.

It is well known that sand castings of long freezing range alloys do not exhibit the type of centerline shrinkage porosity that is common in steel castings. This is also (indirectly) stated by Sigworth. Hence, we included in our study an example for a magnesium-based alloy (AZ91) that has a long freezing range. As shown in Figure 9(c) of Reference 1, for the case of a sand mold, our modified Niyama criterion indeed predicts very little shrinkage porosity, even though the plate that was simulated is very long and thin. Only near the center of the plate is there an extended region where porosity volume fractions of up to 1 pct are predicted. Although still unpublished, we have recently cast AZ91 plates in a sand mold, and indeed we found such small porosity fractions on metallographic sections. Figure 9(d) in Reference 1 shows corresponding simulation results for the case of a steel mold. Here, traditional centerline shrinkage porosity is predicted by our modified Niyama criterion. Sigworth states that the dimensionless freezing range for long freezing range alloys made in metal molds is 10 to 100 times less than for sand castings of the same alloy. Bearing this in mind while viewing Table I of Sigworth's Discussion, it is seen that the dimensionless freezing range for long freezing range alloys in metal molds can be similar to values for steel sand castings. Thus, we believe that our results for the AZ91 alloy are realistic and lend further support to our pressure drop and modified Niyama criterion calculations in general.

The third question raised by Sigworth is whether our modified Niyama criterion can be used to predict the amount of porosity formed. As already mentioned, for steel sand castings, we present in Reference 1 direct experimental validation of our shrinkage porosity volume fraction predictions (Figure 8). We do not understand why Sigworth does not consider this evidence in his Discussion. While the agreement between measured and predicted porosity volume fractions is not perfect, it is impressive considering the many approximations made in the Niyama calculations.

Sigworth then states that the amount of porosity is primarily controlled by the cooling rate and by the gas content. He should have mentioned that his previous studies on this topic all dealt with hydrogen gas porosity in aluminum castings. We would like to refer Sigworth to a recent study of such porosity,[8] where we found that gas porosity is indeed controlled by those two factors and that the pressure drop does not play a role (at least for the aluminum castings investigated, where the Niyama criterion value was sufficiently high to prevent additional shrinkage porosity). It is unfortunate that shrinkage porosity and gas porosity continue to be confused. The Niyama criterion does not predict gas porosity; in fact, it shows the wrong trend with the cooling rate, as noted in Reference 8. In Reference 8, we present a model that is valid for both shrinkage and gas porosity and that accurately predicts the measured gas pore volume fractions shown in Figure 4 in the Discussion by Sigworth. Again, such gas porosity has no relevance in the present discussion of the Niyama criterion.

REFERENCES

1. C. Carlson and C. Beckermann: *Metall. Mater. Trans. A*, 2009, vol. 40A, pp. 163–75.
2. K.D. Carlson, S. Ou, R.A. Hardin, and C. Beckermann: *Metall. Mater. Trans. B*, 2002, vol. 33B, pp. 731–40.
3. R. Hardin, T. Hays, and C. Beckermann: *Proc. 55th Technical and Operating Conf.*, SFSA, Chicago, IL, 2001.
4. S. Ou, K.D. Carlson, and C. Beckermann: *Metall. Mater. Trans. B*, 2005, vol. 36B, pp. 97–116.
5. K.D. Carlson, S. Ou, and C. Beckermann: *Metall. Mater. Trans. B*, 2005, vol. 36B, pp. 843–56.
6. K.D. Carlson and C. Beckermann: *Proc. 62nd Technical and Operating Conf.*, SFSA, Chicago, IL, 2008.
7. S. Ou, K.D. Carlson, R.A. Hardin, and C. Beckermann: *Metall. Mater. Trans. B*, 2002, vol. 33B, pp. 741–55; also *Feeding & Risering Guidelines for Steel Castings*, SFSA, Chicago, IL, 2001.
8. K.D. Carlson, Z. Lin, and C. Beckermann: *Metall. Mater. Trans. B*, 2007, vol. 38B, pp. 541–55.