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Round Robin Study to Assess Variations in Casting Simulation Niyama Criterion Predictions

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Abstract

The Niyama criterion, a local thermal parameter that is a common output of casting simulation software packages, is frequently used to predict shrinkage porosity defects in steel castings. Previous studies indicate that it is a robust parameter that not only predicts the macro-shrinkage that is visible on radiographs, but also smaller micro-porosity that is usually not detectable using standard radiographic techniques. The implication of this previous work is that the Niyama criterion values from a casting simulation may be used not only to provide guidance in designing shrinkage-free steel castings, but also as a quality measure in a purchase specification. Before the Niyama criterion can be used in this manner, it is important to establish a method that assures that the Niyama values are predicted in a reliable and reproducible way that does not depend on the casting simulation software itself, or on its internal or user settings. The objective of the present study is to assess variations in Niyama predictions among various casting simulation software packages and users, for a given casting. Fifteen SFSA member foundries simulated the solidification of a common casting geometry, using up to four cast alloys (WCB, CF-8M, CN-7M and M-30C). Niyama criterion results produced from these simulations are evaluated and compared, and the causes of the sometimes significant variations among the Niyama values are analyzed. The sensitivity of the Niyama predictions to numerical grids, location within the casting, variations in the Niyama evaluation temperature, and differences in thermophysical property data are investigated. In addition, the results from two common casting simulation software packages are compared using, as much as possible, the same properties and settings. From the various investigations performed in this study, it is ascertained that differences in the thermophysical properties of the metal alloy used in the simulation most significantly affect the Niyama predictions. Therefore, if the Niyama criterion were to be used in a purchase specification, it must be ensured that a "good" property dataset is used.

1. Introduction

The Niyama criterion, defined as the local thermal gradient divided by the square root of the cooling rate (i.e., $Ny = \sqrt{G/\dot{T}}$), is a commonly used output variable in casting simulation software packages to predict shrinkage porosity defects in steel castings. Shrinkage porosity is likely to occur if the calculated Niyama value is below a certain critical value. Previous studies[1-7] by the University of Iowa have shown that feeding distances, for example, can be reliably predicted using the Niyama criterion. Case studies[8] have indicated that the Niyama criterion also correlates with the occurrence of some leakage defects in fluid containing low- and high-alloy castings. Evidence exists[8,9] that the Niyama criterion not only predicts the macro-shrinkage that is visible on radiographs, but also smaller micro-porosity that is usually not detectable on standard radiographs used in the foundry industry.

This previous work indicates that the Niyama criterion values from a casting simulation may be used to not only provide guidance in designing shrinkage-free steel castings, but also as a quality measure in a purchase specification (in addition to other specifications). By requiring the Niyama values in an area of a casting to be above a certain critical value, the absence of shrinkage porosity could perhaps be assured. This would not be unlike setting an ASTM standard x-ray level requirement for a casting.

Before the Niyama criterion can be used in this manner, it is important to establish a method that assures that the Niyama values are predicted in a reliable and reproducible way that does not depend on the casting simulation software itself or its internal or user settings. Ideally, for the same casting alloy, geometry and process, the same Niyama values should be predicted. Unfortunately, unlike simple physical measurements (such as temperature), casting simulation is a complex process that requires much user input. Some of the critical issues in the prediction of the Niyama criterion value are: (i) some software may provide inaccurate predictions due to the nature of the numerical approximations made internally; (ii) different software may evaluate the Niyama criterion differently (e.g., units used, temperatures at which the thermal gradient and cooling rate are evaluated); (iii) the thermophysical properties of an alloy/mold material, which are needed in a casting simulation, may not be well established; if different properties are used, the predicted temperatures and, hence, the Niyama criterion values will be different; (iv) the casting and boundary conditions may not be accurately known or input (pouring temperature, mold/metal interfacial heat transfer coefficient, ambient heat transfer, etc.); (v) the choice of the numerical grid and time steps will depend on the software user and available computing power.

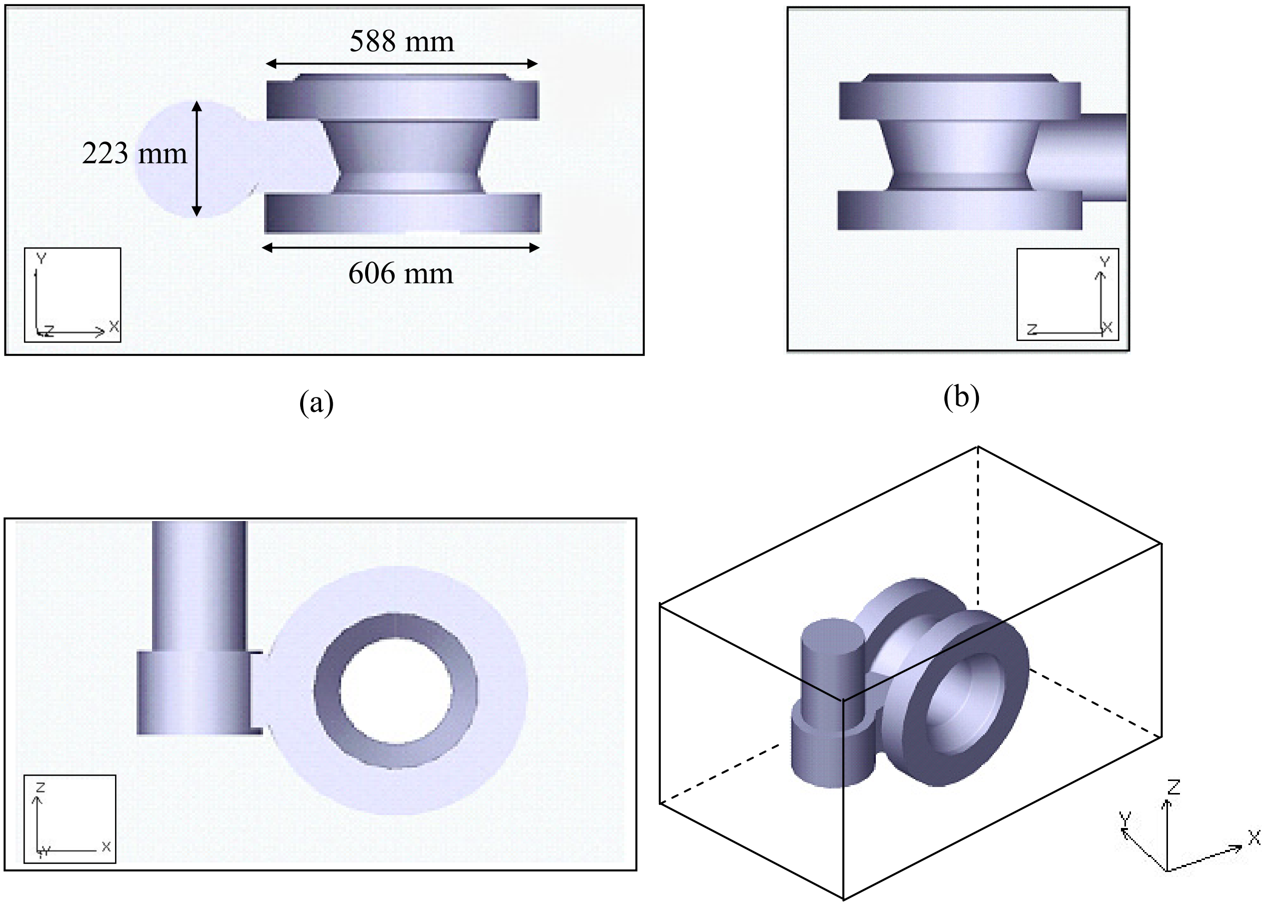
The objective of the study is to conduct a round robin testing program among SFSA steel foundries to assess the variations in the Niyama predictions among various casting simulation software packages and users, for a given casting. The study includes four different cast alloys: WCB, CF-8M, CN-7M and M-30C.

This article details the round robin study procedures, and then presents the results obtained from the study. For each of the four alloys, the results are compared in order to assess the variations in the Niyama predictions among the various software packages, as well as among various users of the same package. In addition, a section that analyzes the sensitivity of Niyama predictions to position, number of metal cells and Niyama evaluation temperature is also included. Finally, in order to assess the importance of the modeling and numerical approximations inherent in casting simulation software, Niyama predictions from different simulation packages using a common material property steel dataset are compared and evaluated. Conclusions and recommendations are made from the various investigations and findings in the study and presented in the last section of this article.

2. Round Robin Test Procedures

Simulation Procedure

This section explains the procedure followed by the participants of the round robin study. The procedure detailed here was explained in a description sheet, which was provided to all round robin study participants. The valve geometry shown in figure 1 was selected as the casting to be used by all participants in this study. To provide a sense of scale, the diameters of the valve flanges are about 23 inches, and the diameter of the riser is about 9 inches. CAD files for the mold box, riser and valve geometry were created and provided to all participants for use in their simulations, in order to ensure that all participants began with the same geometry. It was decided that participants would perform a solidification-only simulation for this study (i.e., no filling simulation), in order to remove any variation caused by differences among filling simulations.



(a) (b)

(c) (d)

Figure 1. Views of the valve geometry

The participating organizations were instructed to use pep-set sand mold properties, assuming the use of hot topping on the riser. They were asked to conduct the simulations on as many of the following four metal alloys as they had material property data for: WCB, CF-8M, CN-7M and M-30C. The following table lists the superheat values (difference between the initial metal temperature specified in the simulation and the liquidus temperature of the alloy) that the participants were instructed to use while conducting the simulations.

Table 1. Superheat values for the alloys included in the study

Alloy	Superheat value (°C)
WCB	20
CF-8M	100
CN-7M	100
M-30C	100

Preparation of the Results

The results were collected in the form of Niyama contour plots given at cross-sectional slices (in the XZ-plane, see figure 1c) at three locations in the valve, as shown in figure 2. In order to produce the plots, the participants were asked to use their best judgment in choosing a scale for the Niyama plots.

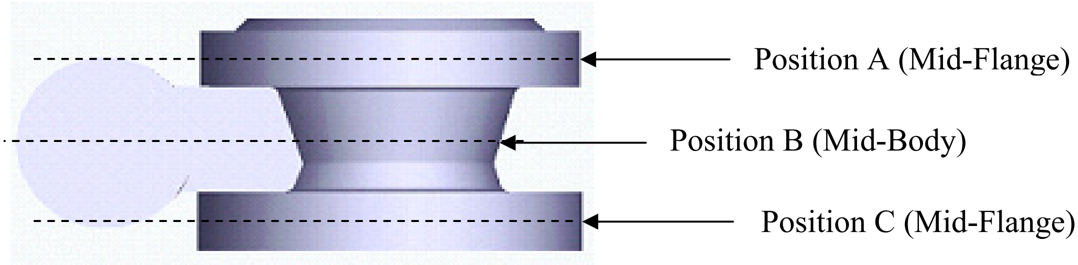


Figure 2. Slice locations at which the results were requested

In addition to the preparation of the Niyama plots, the participants documented necessary simulation details in a simulation data sheet that was provided to them. The details included the name of the simulation package used, number of metal cells or metal elements used for the simulations, and the units of the Niyama criterion in the simulation package used. Also, for each alloy simulated, participants provided the values of the liquidus temperature (T_{liq}), the temperature at which the metal is 100% solid (T_{sol}), and either the temperature at which the Niyama criterion was evaluated (T_{Ny}) or where in the solidification range ($T_{liq} - T_{sol}$) the Niyama criterion was evaluated (for example, 10% of the solidification range above the temperature at which the metal is 100% solid).

3. Niyama Plots from The University of Iowa

This section displays Niyama plots at the slices indicated in figure 2, for all four alloys, obtained using MagmaSoft at The University of Iowa. Table 2 shows characteristic temperature values that were used in the simulation of each alloy. The first three columns are taken from material datasets, while the fourth is a user-specified value. The WCB dataset represented in table 2 is the standard MagmaSoft WCB dataset (named 'GS24Mn4'). The CF-8M dataset was developed by the present researchers using the software package IDS, developed by Miettinen *et al.*,[10,11] which simulates the microsegregation and phase transformations that occur during low-alloy and stainless steel solidification. IDS also calculates all of the other material properties required as input for casting simulation software (density, thermal conductivity, etc.). The CN-7M and M-30C datasets were developed by the present researchers using the software package JMatPro,[12] which calculates the solidification path and all casting-relevant material properties for a given alloy composition, using thermodynamic databases for certain classes of alloys. Experimental temperature measurement data for these alloys, indicating liquidus and 100% solid temperatures, was used to fine-tune parameter settings in the JMatPro simulations.[5,7] The Niyama criterion evaluation temperatures listed in the last column of table 2 are the MagmaSoft default values for each alloy, where the default Niyama evaluation temperature is 10% of the solidification interval above the 100% solid temperature [i.e., $T_{Ny} = T_{sol} + 0.1(T_{liq} - T_{sol})$].

Table 2. Temperature values used by The University of Iowa

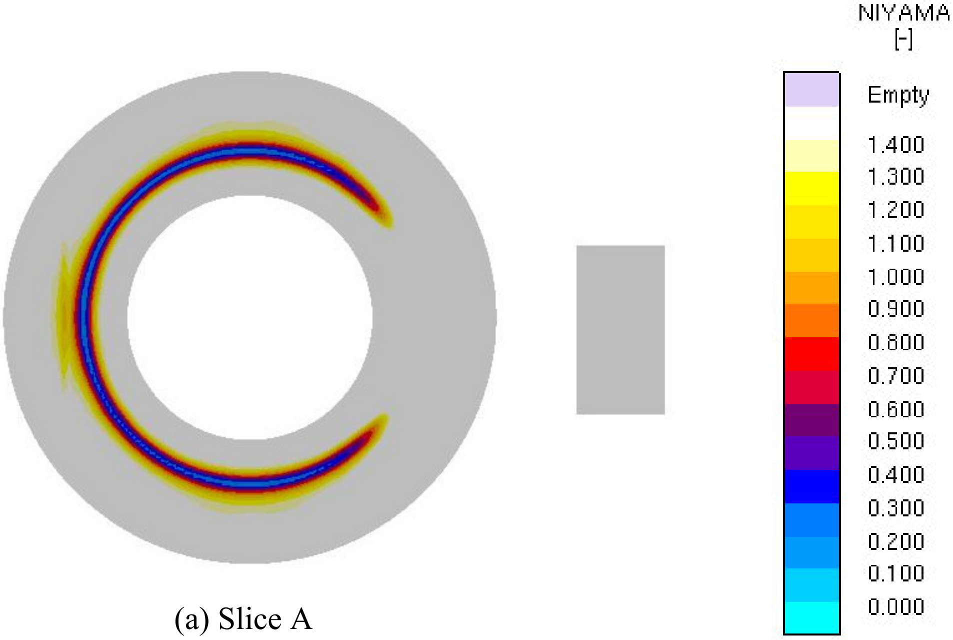
Metal Alloy	**Liquidus Temperature, T_{liq} (°C)**	**100% Solid Temperature, T_{sol} (°C)**	**Solidification Range, $(T_{liq} - T_{sol})$ (°C)**	**Niyama Evaluation Temperature, T_{Ny} (°C)**
WCB	1519	1412	107	1423
CF-8M	1430	1320	110	1331
CN-7M	1393	1300	93	1309
M-30C	1303	1193	110	1204

For The University of Iowa simulations, all four of the alloys listed in table 2 were paired with the sand database 'FURAN' from MagmaSoft, which models a resin-bonded silica sand. The heat transfer coefficient specified between alloy and mold for all alloys was 'C800' from the MagmaSoft database, which is a constant heat transfer coefficient of 800 W/m^2-K. All four simulations were based on the same numerical grid, which was generated using MagmaSoft's automatic grid generation with approximately 2 million control volumes. This produced a mesh that contains a total of 1,956,930 computational cells, of which 439,039 are cells located in the casting or riser ('metal cells') and the remainder of the cells are located in the mold ('mold cells'). The initial temperatures used for each alloy were determined by adding the superheat values listed in table 1 to the liquidus temperatures listed in table 2.

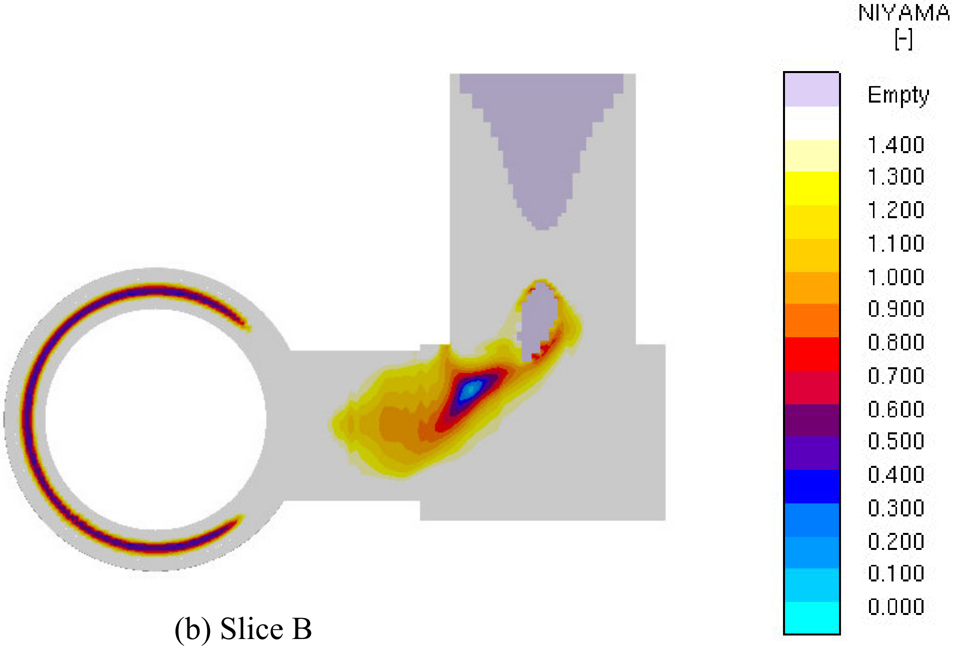
Niyama Plots for WCB

Figures 3a to 3c show Niyama plots for WCB. These plots were obtained at the cross-sectional locations ("slices") indicated in figure 2, in the center of each flange and the center of the valve body. The units for the Niyama values shown below are (°C-s)$^{1/2}$ /mm. The scale of 0 to 1.4 shown in these figures was chosen because low Niyama values in this range are known to correlate to shrinkage porosity defects. The white regions of these plots have Niyama values greater than 1.4 (°C-s)$^{1/2}$ /mm.

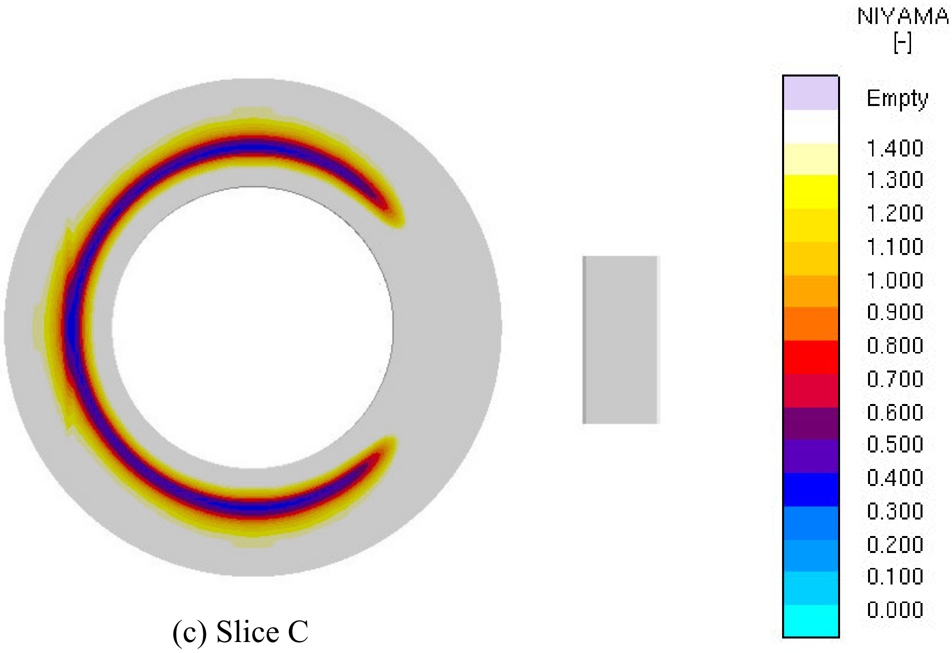
The plots in figure 3 each show a C-like region of Niyama values in the range of 0 to 1.4 (°C-s)$^{1/2}$ /mm (0 to 1.08 (°C-min)$^{1/2}$ /cm). In Slice B, the Niyama indications to the right of the valve body are associated with the secondary shrinkage below the riser pipe. Compared to Slice A, the Niyama variation in Slice C occupies a wider region, containing slightly higher Niyama values.



(a) Slice A



(b) Slice B

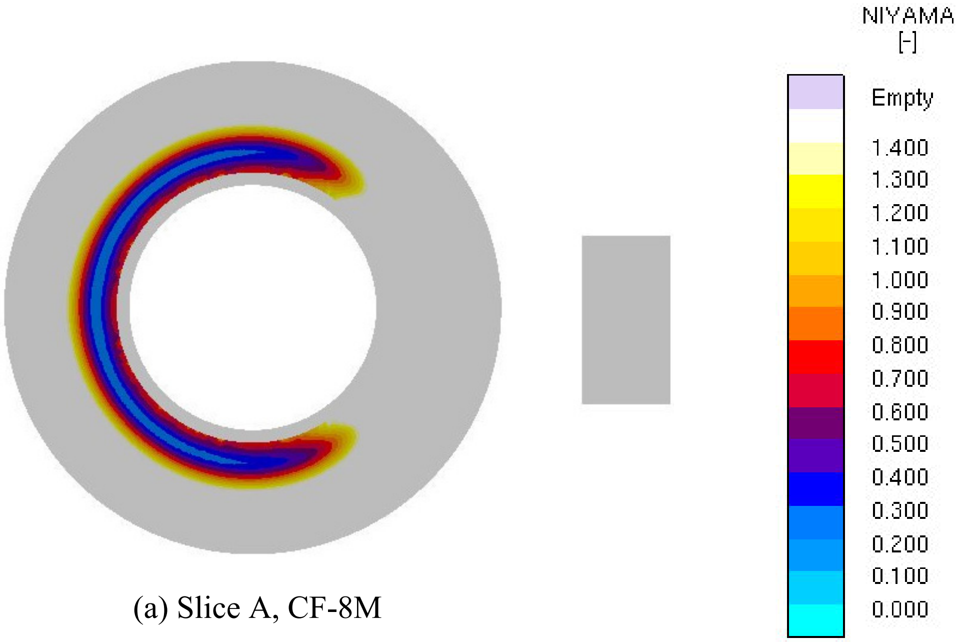


(c) Slice C

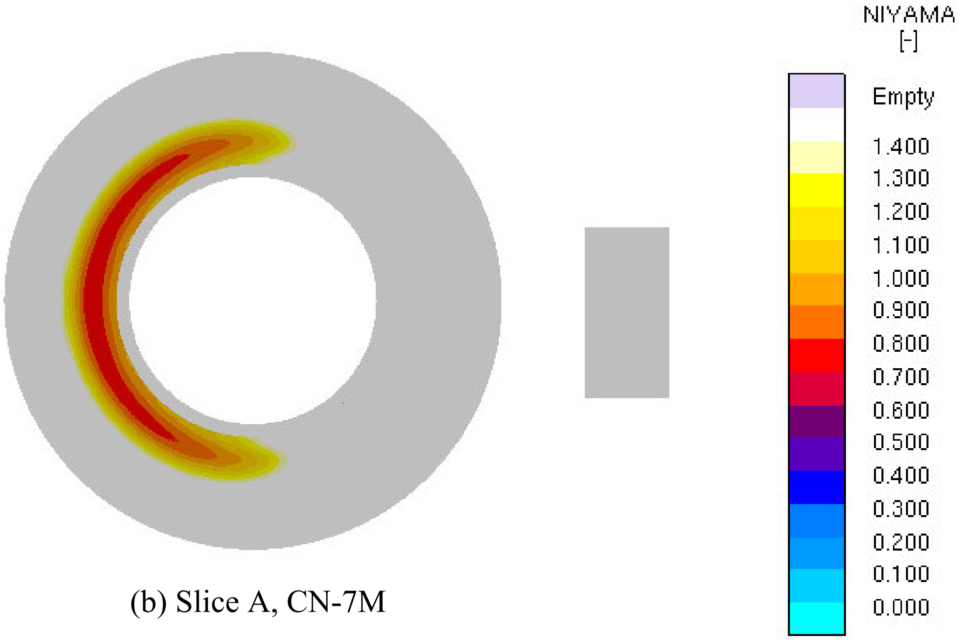
Figure 3. Slices showing Niyama plots from MagmaSoft WCB simulation

Representative Niyama Plots for CF-8M, CN-7M and M-30C

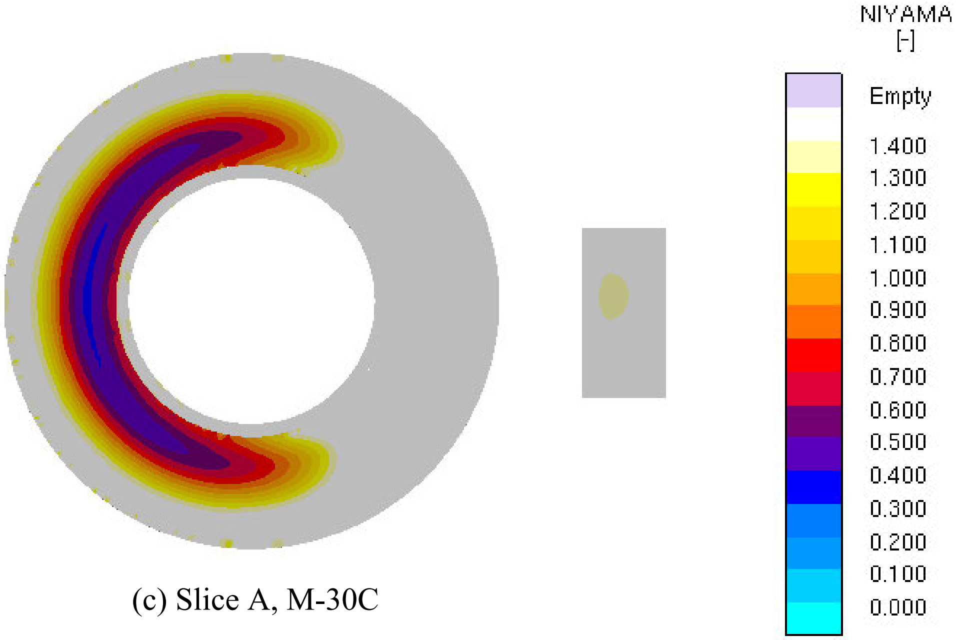
Figure 4 shows Niyama plots obtained for Slice A (as indicated in figure 2), for the alloys CF-8M (figure 4a), CN-7M (figure 4b) and M-30C (figure 4c). The units for the Niyama values shown below are $(°\text{C-s})^{1/2}$ /mm. Compared to the WCB results, the Niyama values for the CF-8M slices are somewhat higher, and the Niyama band is closer to the inner diameter surface. The Niyama values in the CN-7M plot are notably higher than in the previous two alloys. Finally, the M-30C Niyama values are relatively similar in magnitude to those of CF-8M. A notable aspect of the M-30C Niyama contours is that the colored region is very wide, spanning much of the width of the casting section shown.



(a) Slice A, CF-8M



(b) Slice A, CN-7M



(c) Slice A, M-30C

Figure 4. Niyama plots for Slice A from MagmaSoft simulations for (a) CF-8M, (b) CN-7M and (c) M-30C

4. Results of the Round Robin Study

Number of Responses Received

Simulation results were received from 15 organizations, each of which used one (or more) of the following three software packages: SolidCast, MagmaSoft or Flow3D. The following table shows the number of organizations using each package, along with the number of simulation results for each of the alloys.

Table 3. Number of responses received

Simulation Package	**Niyama Criterion Units**	**Number of Organiza-tions Using Package**	**WCB Simu-lations**	**CF-8M Simu-lations**	**CN-7M Simu-lations**	**M-30C Simu-lations**
SolidCast	(°C-min)$^{1/2}$ /cm	7	6	5	1	1
MagmaSoft	(°C-s)$^{1/2}$ /mm	7	7	4	1	0
Flow-3D	(°C-min)$^{1/2}$ /cm	2	1	2	1	1
	Total	16*	14	11	3	2

* One of the organizations used two software packages.

As table 3 indicates, the number of CN-7M and M-30C simulations is very low, since most participants did not have material property data for these alloys. Hence it is difficult to make any definite conclusions from their analysis. Note that the Niyama criterion units are related by the conversion: 1 (°C-s)$^{1/2}$ /mm = 1.29 (°C-min)$^{1/2}$ /cm.

Method of Reading Minimum Niyama Values

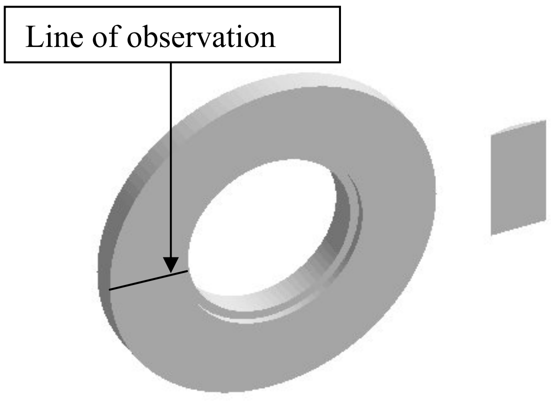
Once all of the simulation results were obtained, qualitative comparison of the Niyama plots indicated similar trends (the C-like ring of low Niyama values in each slice, for example). However, it is difficult to rigorously compare the results in this manner due to the different scales used by different users, and due to the different color schemes and units used by the different software packages. In order to make a quantitative comparison of these results, it was decided to compare minimum Niyama values in certain regions of the slices. In particular, for each of the results provided by the participants of this study, the minimum Niyama value was read along a line of observation located at mid-height of the valve, as shown in figure 5.

All of the minimum Niyama criterion values that were read from the results were converted to common units ((°C-s)$^{1/2}$ /mm), in order to obtain a common basis for comparison. For each of the four alloys simulated, and for each slice showing Niyama predictions, bar graphs showing the Niyama values were plotted and analyzed. Because Niyama values from participants were being determined using the contour plots they provided (by determining the color band containing the minimum value, and using the mean value of that color band), there is some uncertainty in the values shown in the upcoming graphs, since the true value may be anywhere between the upper and lower bounds of the color band. This uncertainty is indicated with vertical error bars in the bar graphs.

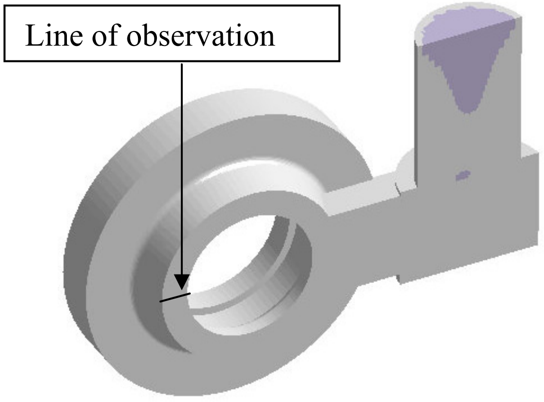
To maintain the anonymity of the participating organizations, an identification tag ('result ID') was assigned to each organization, where the number denotes the organization and the letter denotes the first letter of the simulation package used. So, for example, result ID 1-S indicates organization 1 with results from SolidCast. The result ID UI-M represents values from the present researchers (The University of Iowa), obtained using MagmaSoft.

Comparison of WCB Results

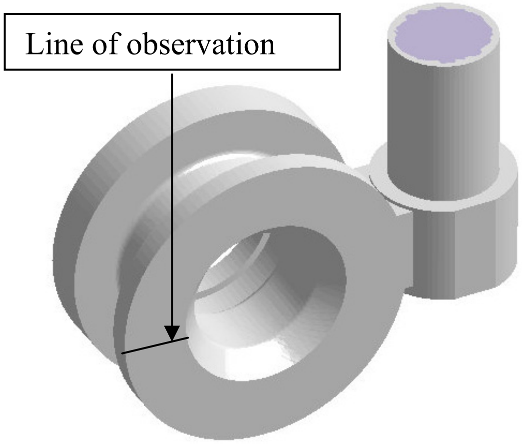
In order to get an idea of the variance in material properties used for WCB steel in the simulations performed for this study, table 4 lists several important characteristic temperature values from the datasets that were used by each organization.



(a) Representative Slice A – Iso view



(b) Representative Slice B – Iso view



(c) Representative Slice C – Iso view

Figure 5. Representative slices showing line of observation

Table 4. Characteristic values for WCB simulations performed by participants

Result ID	**Liquidus Temperature, T_{liq} (°C)**	**100% Solid Temperature, T_{sol} (°C)**	**Solidification Range, $(T_{liq} - T_{sol})$ (°C)**	**Niyama Evaluation Temperature, T_{Ny} (°C)**	**Number of Metal Cells Used**
1-S	1510	1466	44	1482	2,000,000*
2-S	1510	1465	45	1480	3,594,240*
3-S	1543	1521	22	1528	529,846*
4-S	1540	1413	127	1496	4,173,525*
5-S	not provided	not provided	not provided	65% solidified	199,584*
6-S	1519	1412	107	1435	1,000,000*
11-F	1510	1466	44	1482	2,000,000*
6-M	1519	1412	107	1423	439,039
8-M	1519	1412	107	1423	1,381,717
9-M	1519	1412	107	1410	1,678,502
10-M	1519	1412	107	1423	605,780
13-M	1519	1412	107	1425	138,401
14-M	1519	1412	107	1422	439,039
15-M	1519	1412	107	1423	439,039
UI-M	1519	1412	107	1423	439,039

* This number is likely the total number of computational cells, not the number of metal cells. The number of metal cells is probably smaller than the total number of cells by about a factor of four or five.

Note in table 4 that the first three columns of temperatures listed for MagmaSoft users are identical; this is because MagmaSoft contains a property dataset for WCB (named ‘GS24Mn4’), which all users appear to have utilized. On the other hand, SolidCast users did not report the same set of temperature values for WCB simulations; SolidCast does not provide material datasets, so users must supply this information themselves. Organization 6, which has both MagmaSoft and SolidCast, used the same solidification range for SolidCast as for MagmaSoft. They probably took the WCB data for SolidCast from the MagmaSoft database. However, the Niyama evaluation temperature for 6-S is different than for 6-M. Note in table 4 the variation in the solidification ranges when users must supply their own material data: organization 3-S has a very small solidification range of 22°C, whereas organization 4-S has a comparatively large solidification range of 127°C. Also note that there is a very significant 33°C spread in the liquidus temperature values. It is important to point out that the differences in these solidification ranges are indicative of differences in all material properties, including solid fraction variation as well as other thermophysical properties. Differences in these temperatures also affect the Niyama evaluation temperatures, which are typically determined using the solidification range. The MagmaSoft default value (10% of the solidification range above the 100% solid temperature) is 1423°C for this alloy; this value was used by all but three of the participants using MagmaSoft. Organizations 13-M and 14-M used values within a degree or two of the default value, while organization 9-M reported its Niyama evaluation temperature as 1410°C, a value below the 100% solid temperature. SolidCast recommends that its users set the Niyama evaluation temperature to the value where the material is 65% solidified (i.e., 35% of the solidification range above the 100% solid temperature). This was done by organizations 1-S, 2-S, 3-S and 5-S (organization 5-S did not provide the requested temperatures, but did indicate that the default Niyama evaluation temperature was used). A temperature above the recommended value was utilized by organization 4-S, while one below the recommended value was used by 6-S. Organization 11-F has the same temperature values as organization 1-S, and also uses a Niyama evaluation temperature 35% of the solidification range above the 100% solid temperature.

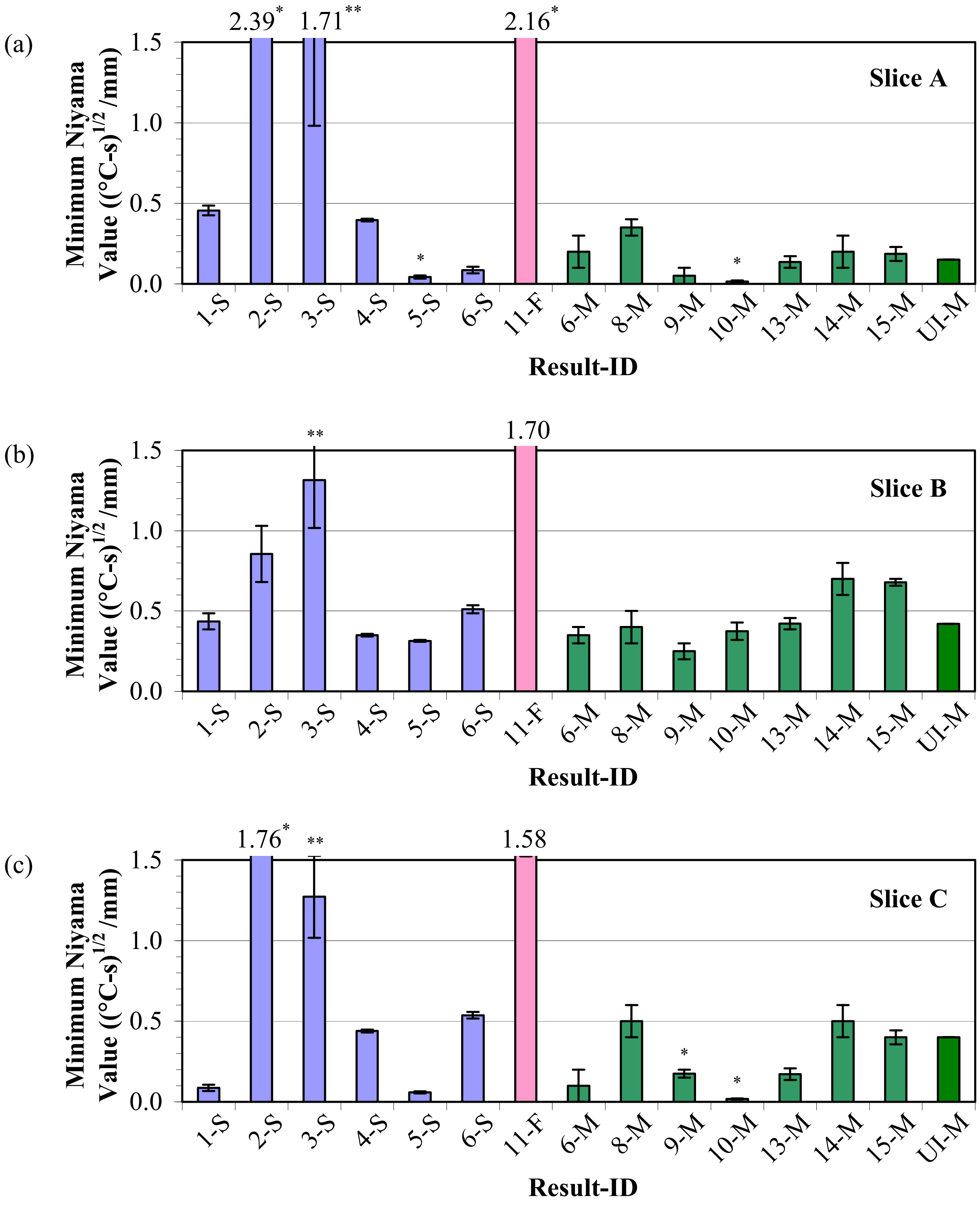
Table 4 also includes the number of metal cells used by each participant in their simulation. Discussion with SolidCast users indicates that SolidCast provides the total number of computational cells, but not the number of metal cells. So the number of cells listed for SolidCast users in table 4 is probably about four or five times larger than the number of metal cells. It is uncertain if the value given by the Flow-3D user is metal cells or total cells, but total cells is likely. Considering this, most organizations utilized between about 140,000 and 1,000,000 metal cells in their simulations. The UI value was chosen to be a median value in this range, and to match the value used by three of the other seven MagmaSoft users.

Figure 6 shows the variation in the Niyama predictions for the WCB simulations, for each of the slices (Positions A, B and C shown in figure 2). Numbers above the graphs are used to indicate the value if it exceeds the vertical axis scale. Error bars show the uncertainty in the values. No uncertainty bars are necessary for the UI-M results because these simulations were performed by the present researchers, who refined the Niyama scales during analysis to achieve a high degree of accuracy in the minimum values. Note that for all three slices, organization 11-F has values that are significantly higher than most. Discussion with this user indicates that he used simulation settings typical for centrifugal castings, which involve mold properties and heat transfer coefficients that are significantly different from typical sand castings. This could explain the large 11-F values seen in figure 6. Organizations 2-S and 3-S also have values that are higher than average. Organization 3-S modeled WCB with the small solidification range of 22°C. It is possible that the large Niyama values are a result of the material properties used in this simulation. The effect of material properties on the minimum Niyama value will be explored later in this study. The 3-S results also have a large uncertainty, due to the results being reported with a broad Niyama scale (0 to 22.81 $(°C\text{-min})^{1/2}$ /cm). Organization 2-S has very high values in Slices A and C (figure 6a and 6c), but a value closer to that of the other organizations for Slice B. As denoted by the asterisks, the 2-S results in Slices A and C were taken from slices that were not at the middle of the flanges. This was determined by observing the size of the cross-sectional slice of the riser that appears in the reported results; for example, see the rectangles to the right of the valve flange in figures 3a and 3c. If the width of these riser cross-sections are notably different than those shown in figures 3a and 3c, it indicates that the results were taken from a position away from the center of the flange. To better understand this, consider figure 2: if the dashed lines indicating the positions of Slices A and C are moved up or down in this figure, the amount of the riser that appears in these slices will change. It will be shown in Section 5 that the y-position within the flanges from which the results are taken can significantly affect the minimum Niyama value.

With the exception of the cases discussed above and the other values in figure 6 denoted with an asterisk, note that there is moderate agreement among the SolidCast and MagmaSoft values. The remaining variation in these results is due to one or more of the following: simulation package used, numerical grid, alloy properties, mold properties, heat transfer coefficients, exact slice location where the results were taken, and Niyama evaluation temperature. Considering this, it is interesting to compare the results from MagmaSoft simulations 6-M, 14-M, 15-M and UI-M. These simulations all used the same simulation package, numerical grid, alloy properties, and Niyama evaluation temperatures (the temperature used by 14-M differs from the others by one degree Celsius). Furthermore, the slice location may have a small effect, but it is likely not a big factor, as all of these results appeared to be reasonably close to the correct locations. Accounting for the uncertainty, these results agree relatively well, except that the Slice B values for 14-M and 15-M are somewhat higher than the 6-M and UI-M values. These differences may be due to differences in mold properties or heat transfer coefficients selected by the users, neither of which were reported in this study.

Comparison of CF-8M Results

The important characteristic temperature values used by each organization in their CF-8M simulations are listed in table 5. Again, these numbers provide an idea of the amount of variability in the CF-8M material property data that was used for this study. Table 5 indicates that there is substantial variation in the temperature values used by the participating organizations while conducting their CF-8M simulations. The solidification range varies from values as low as 28°C to as high as 210°C. Both Flow-3D users report the same liquidus temperature value, but there are large differences in the 100% solid and Niyama evaluation temperatures. MagmaSoft users 6-M, 8-M and 14-M all have the same temperature ranges, which matches the range given for the standard MagmaSoft CF8 database (named ‘GX6CrNi18_9’). Again, organization 6 probably used the MagmaSoft properties from this dataset in their SolidCast simulation, since 6-S has the same temperatures as 6-M (however, the Niyama evaluation temperatures are again different for 6-M and 6-S). As discussed in Section 3, the dataset used by The University of Iowa was developed using IDS.[10,11] As with WCB, the differences in temperature ranges indicate not only broader differences in material properties, but also differences in the Niyama evaluation temperatures.



[*] Result not reported at the middle of the flange
[**] Scale used for results was too large to determine value accurately

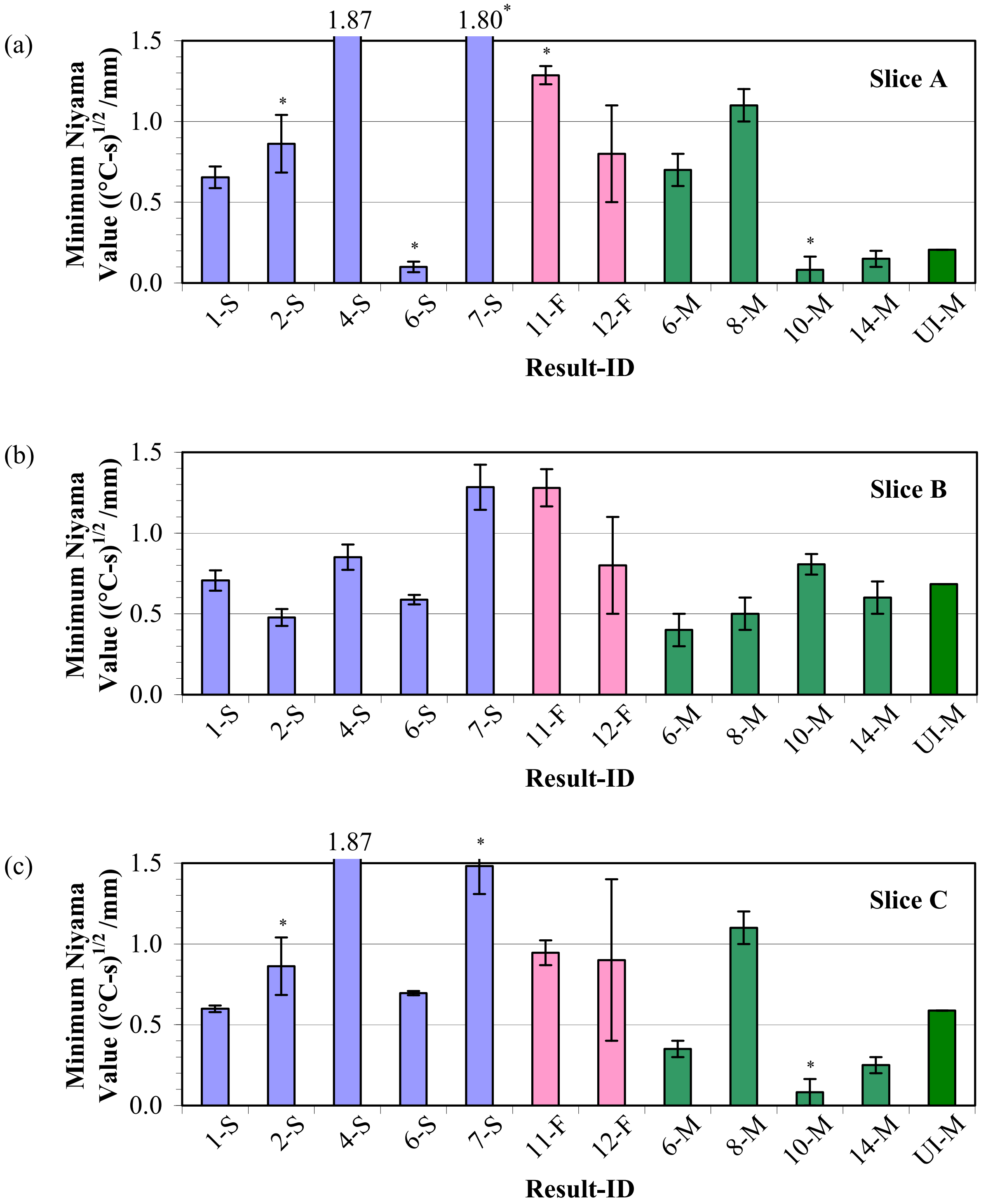
Figure 6. Graphs showing minimum Niyama values obtained from all WCB simulation results

Table 5. Characteristic values for CF-8M simulations performed by participants

Result ID	Liquidus Temperature, T_{liq} (°C)	100% Solid Temperature, T_{sol} (°C)	Solidification Range, $(T_{liq} - T_{sol})$ (°C)	Niyama Evaluation Temperature, T_{Ny} (°C)	Number of Metal Cells Used
1-S	1399	1371	28	1385	2,000,000*
2-S	1400	1370	30	1383	3,594,240*
4-S	1530	1320	210	1456	4,173,525*
6-S	1454	1399	55	1423	1,000,000*
7-S	1482	1371	111	1382	not provided
11-F	1420	1375	45	1394	2,000,000*
12-F	1420	1275	145	1275	1,064,880*
6-M	1454	1399	55	1405	439,039
8-M	1454	1399	55	1405	1,381,717
10-M	1432	1318	114	1329	605,780
14-M	1454	1399	55	1399	439,039
UI-M	1430	1320	110	1331	439,039

* This number is likely the total number of computational cells, not the number of metal cells. The number of metal cells is probably smaller than the total number of cells by about a factor of four or five.

Figure 7 shows the variation in the Niyama predictions for the CF-8M simulations. This figure shows that, as with WCB, there is significant variation in the minimum Niyama values from these simulations. The values in figure 7 from organizations 4-S and 7-S are higher than all other reported values in Slices A and C, and higher than average in Slice B. From table 5, it is seen that these two simulations were run with property datasets that are notably different than most: 4-S uses the largest solidification range (210°C) of all participants, and 7-S has a liquidus temperature that is only exceeded by 4-S. Also, in 7-S, Slices A and C were not taken at the center of the flanges. As in the WCB results, the results from 11-F are high, which again may be the result of the use of centrifugal casting mold properties and heat transfer coefficients that are very different from those of sand casting. The 12-F results may also be somewhat high, although it is difficult to be sure because of the large uncertainty. If these values are indeed high, it could be due to property data as well; note that the 100% solid temperature for 12-F is lower than all others by 43°C. In addition, several of the results for Slice A and Slice C were not taken from the center of the flange, which may affect the minimum values. Considering Slice B, however, and neglecting for the moment the results from 4-S, 7-S, 11-F and 12-F for the reasons just stated, one sees reasonable agreement in the minimum values of the remaining SolidCast and MagmaSoft results. Again, differences can be attributed to many things, including different material properties, grids, Niyama evaluation temperatures and heat transfer coefficients. Note that the minimum values from 6-M, 8-M and 14-M (all of which appear to have used the same MagmaSoft dataset for CF-8M) all approximately agree in Slice B, within the uncertainty shown. The result for 14-M is a little higher, which may be the result of that simulation using the 100% solid temperature as the Niyama evaluation temperature, where the other two simulations used the default MagmaSoft value 10% of the solidification range above the 100% solid temperature.



* Result not reported at the middle of the flange

Figure 7. Graphs showing minimum Niyama values obtained from all CF-8M simulation results

Comparison of CN-7M Results

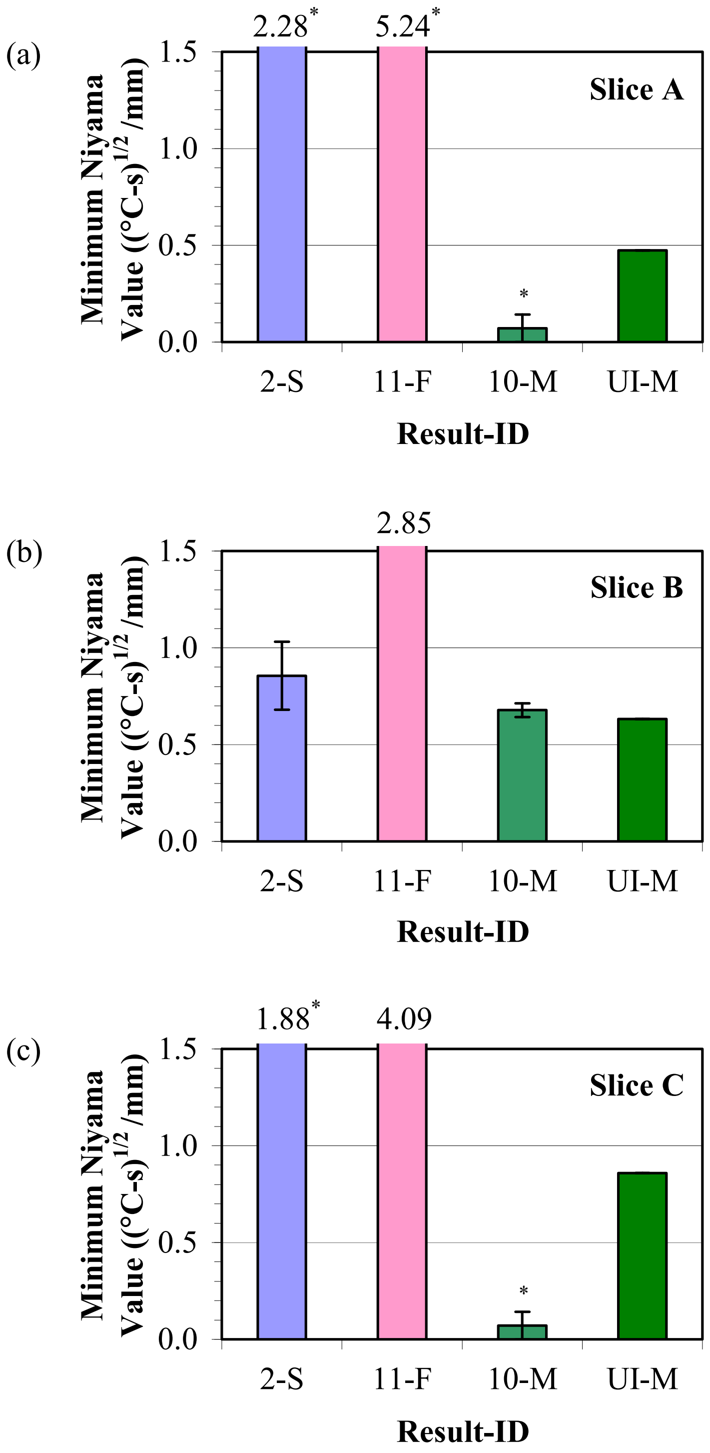
The important characteristic temperature values used by each organization in their CN-7M simulations are listed in table 6. Few organizations simulated CN-7M, since most foundries do not have property data for this alloy. Organizations 2-S and 10-M used very similar temperature values for their CN-7M simulations, including similar Niyama evaluation temperatures. The temperatures from organization 11-F are identical to UI-M values, because 11-F used the CN-7M dataset developed by The University of Iowa in a previous study.[5,6] Organization 2-S used a somewhat finer grid than the other participants listed in table 6, all of which used comparable grids.

Table 6. Characteristic values for CN-7M simulations performed by participants

Result ID	Liquidus Temperature, T_{liq} (°C)	100% Solid Temperature, T_{sol} (°C)	Solidification Range, $\left(T_{liq} - T_{sol}\right)$ (°C)	Niyama Evaluation Temperature, T_{Ny} (°C)	Number of Metal Cells Used
2-S	1400	1370	30	1383	3,594,240*
11-F	1393	1300	93	1309	2,000,000*
10-M	1399	1371	28	1384	605,780
UI-M	1393	1300	93	1309	439,039

* This number is likely the total number of computational cells, not the number of metal cells. The number of metal cells is probably smaller than the total number of cells by about a factor of four or five.

Since the number of CN-7M simulation results is small, it is difficult to analyze the results in an accurate manner. Still, the resulting minimum Niyama values from these simulations are provided in figure 8. As in the previous simulations for WCB and CF-8M, the values for 11-F resulted from simulations that used mold properties and heat transfer coefficients more indicative of centrifugal casting than of sand casting, leading to higher Niyama values compared to all other simulations. The results for 2-S and 10-M in Slices A and C are taken away from the center of the flanges, which may account for differences in these values. However, Slice B shows that the results for 2-S, 10-M and UI-M are all similar, within the uncertainties shown.



* Result not reported at the middle of the flange

Figure 8. Graphs showing minimum Niyama values obtained from all CN-7M simulation results

Comparison of M-30C Results

The important characteristic temperature values used by each organization in their M-30C simulations are listed in table 7, which indicates that all three participants used quite different sets of simulation temperatures (and hence different property datasets) for M-30C. As with CN-7M, few foundries have material property data for M-30C, resulting in very few results for this alloy. The three sets of results listed in table 7 were produced with comparable numerical grids.

Table 7. Characteristic values for M-30C simulations performed by participants

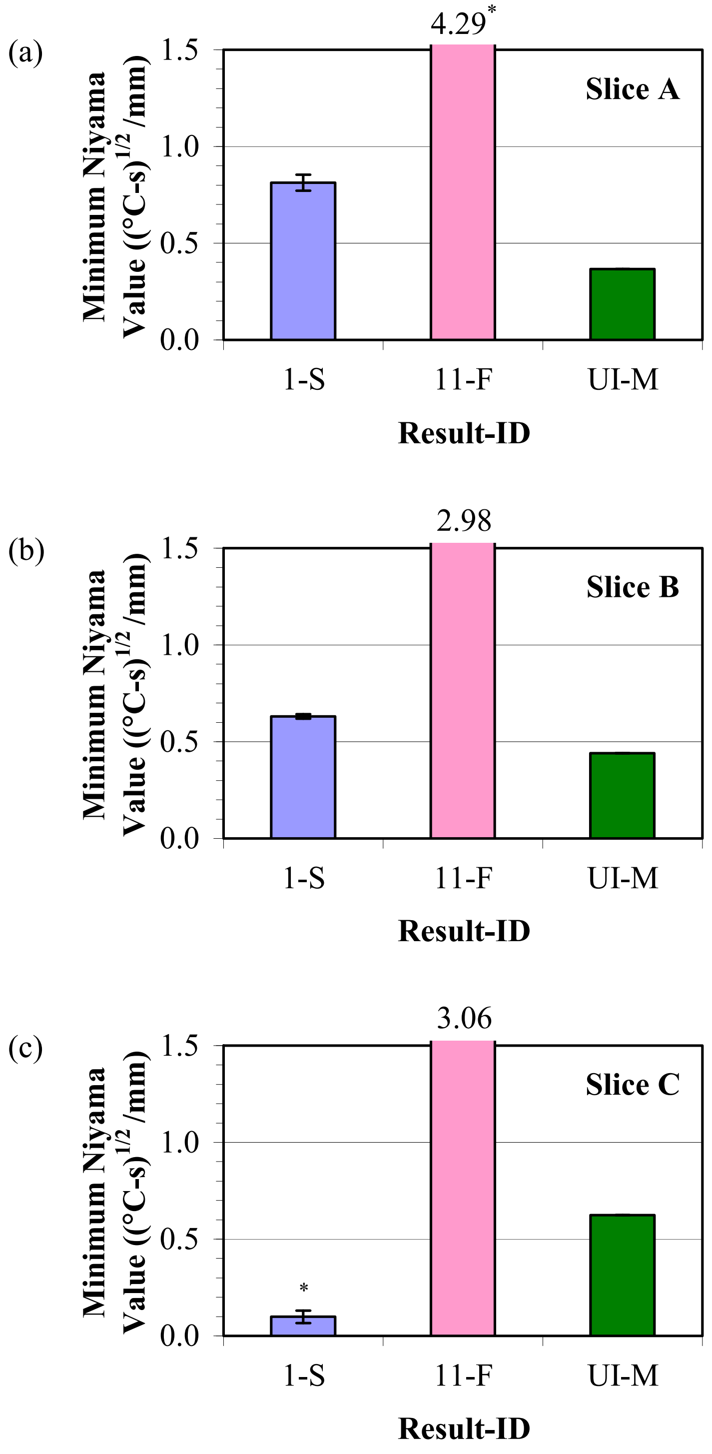
Result ID	**Liquidus Temperature, T_{liq} (°C)**	**100% Solid Temperature, T_{sol} (°C)**	**Solidification Range, $(T_{liq} - T_{sol})$ (°C)**	**Niyama Evaluation Temperature, T_{Ny} (°C)**	**Number of Metal Cells Used**
1-S	1349	1299	50	1316	2,000,000[*]
11-F	1366	1299	67	1333	2,000,000[*]
UI-M	1303	1193	110	1204	439,039

[*] This number is likely the total number of computational cells, not the number of metal cells. The number of metal cells is probably smaller than the total number of cells by about a factor of four or five.

Figure 9 shows the variation in the Niyama predictions for M-30C simulations. As with all other results presented in this section, the 11-F minimum values are higher than the other results, which is likely the result of the mold properties and heat transfer coefficients. The Slice C result from 1-S is not at the center of the flange. The 1-S results are higher than the UI-M results in the other slices (although only a little higher in Slice B), which could be the result of the different material properties, or any of the other possibilities mentioned in this section.

Summary of the Results

The results presented in this section display a significant amount of variability in the minimum Niyama values reported by various participants for each alloy. It is seen that there is a considerable amount of variability in the material properties used by different participants (as shown by the differences in the liquidus temperatures, 100% solid temperatures, and solidification ranges), as well as in the temperature at which the Niyama criterion was calculated. These differences even occur between users of the same simulation package. The variances in material properties and Niyama evaluation temperatures are likely the sources of at least some of the scatter in the minimum Niyama data. Another factor that may contribute to the variability in these results is the exact y-location of the cross-sectional slices that each participant chose for their results; it is evident from several of the Slice A and Slice C Niyama contour plots that the y-location is not quite in the center of the flanges, which was detected by the present researchers by the size of the riser cross-section visible in these plots.



* Result not reported at the middle of the flange

Figure 9. Graphs showing minimum Niyama values obtained from all M-30C simulation results

There are some simulations that have similar enough settings to filter out many of these sources of variability. For example, for WCB, organizations 6-M, 10-M, 14-M, 15-M and UI-M all used the same material dataset, the same or very similar Niyama evaluation temperatures, and the same or similar numerical grids (see table 4). Looking at Slice B in Figure 6 (to eliminate the issue of the exact y-location in the flanges, Slices A and C), one sees that 6-M, 10-M and UI-M are in agreement, but that 14-M and 15-M have noticeably higher minimum Niyama values. This may be caused by differences in sand mold properties or heat transfer coefficients used in these simulations, neither of which were recorded in this study. Note that the minimum Niyama values for 8-M and 13-M, which have a significantly different number of metal cells, are in good agreement with each other and the results for 6-M, 10-M and UI-M. This indicates that the numerical grid does not have a strong influence on the predicted minimum Niyama values. The above analysis lends credibility to the idea that if the same material property data and Niyama criterion evaluation temperature are used, the resulting minimum Niyama values are similar. The following sections further explore the importance of potential sources of variability in Niyama simulation results.

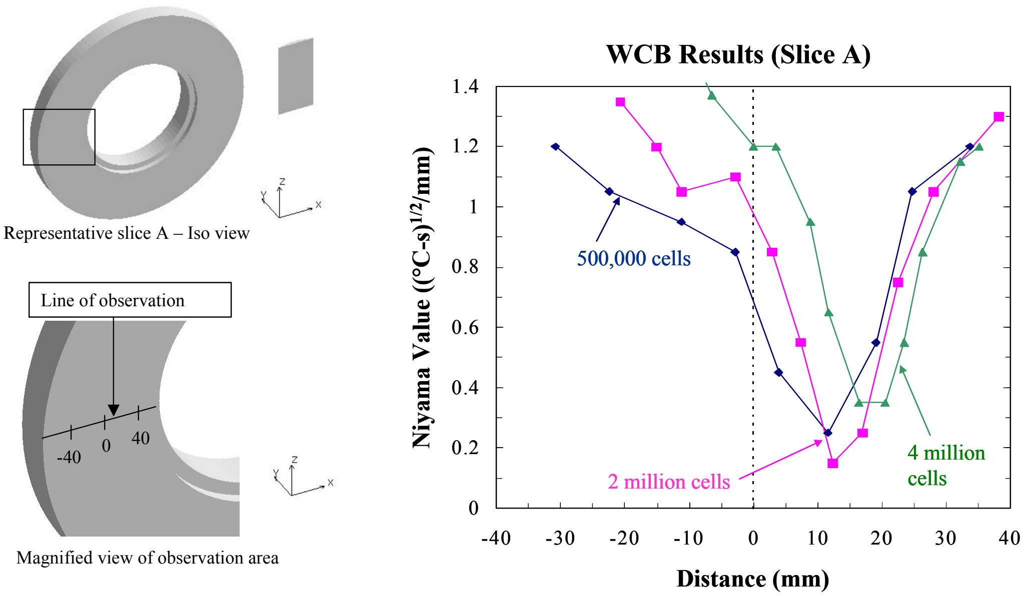
Finally, a potential source of error in the results in this section is the uncertainty in the minimum Niyama values caused by reading the minimum value from contour plots submitted by participants. However, this was accounted for by including error bars in the bar graph results. This uncertainty does indicate that the choice of scale in Niyama contour plots is quite important; if one is interested in the lower Niyama values (in order to detect shrinkage defects), it is necessary to have a sufficiently small scale such that these low values can be resolved.

5. Sensitivity Studies

In order to better understand the differences in the minimum Niyama values from the previous section, sensitivity studies were conducted by the present researchers (using MagmaSoft) in order to assess variations in Niyama predictions with respect to position, number of metal cells and Niyama evaluation temperature.

Sensitivity of Niyama Value Predictions to Different Numerical Grids

The first sensitivity study investigates the sensitivity of the Niyama value to the numerical grid, by studying the Niyama value variation along the x-axis of each slice (A, B and C) for different numerical grids using WCB steel. Figure 10 shows Slice A Niyama variations along a line of observation located mid-height of the valve, for simulations run with three different numerical grids: coarse (~500,000 total computational cells, of which ~100,000 are metal cells), medium (~2 million total cells, of which ~400,000 are metal cells) and fine (~4 million total cells, of which ~900,000 are metal cells). Slice B and Slice C results show similar trends, and thus are not included.



Representative slice A – Iso view

Magnified view of observation area

Figure 10. Niyama variation in Slice A along a line of observation in the XZ plane

These three sets of Niyama results displayed in figure 10 demonstrate that changing the numerical grid may change the location of the minimum Niyama value along the line of observation. However, while their locations may shift, the magnitudes of the minimum Niyama values in each slice are similar for each of the three grids. This indicates that the magnitude of the minimum Niyama value is relatively insensitive to the number of grid cells used in the simulation, which is to be expected at the levels of resolution considered here. Because of this, further sensitivity studies in this section will only use the fine grid (4 million total cells).

Sensitivity of Niyama Value Predictions to Distance Along the Y-axis

In the previous section, it was proposed that differences in the exact y-location where participants recorded Niyama values in Slices A and C may contribute to the variability in the minimum Niyama results. This theory is the result of the present sensitivity study. Figures 11 to 13 indicate Niyama variations along a line of observation perpendicular to the previous one, also located mid-height of the valve, for a simulation using 4 million metal cells.

In figure 12, note that there is very little variation in the minimum Niyama value along the line of observation for Slice B. However, the variation is much more pronounced in Slices A and C (figures 11 and 13). In figure 11, it is seen that the minimum Niyama value changes by almost a factor of three when the location moves from the center of the flange (distance = 0) to a location 10 mm closer to the outside of the flange (distance = -10 mm). This Niyama variation for distances < 0 mm in Slice A could explain some of the variation in the Niyama values collected for Slice A, since several of the Slice A results submitted for this study were taken at distances < 0 mm. The values from slices nearer to the inside of the flange (distance > 0 mm) in figure 11 are more invariant. The variation in minimum Niyama values in Slice C (see figure 13) is even greater than in Slice A. It is evident that results taken away from the actual center of the flange for Slice C could vary considerably in minimum Niyama value. Thus, variations in minimum Niyama values in the flanges (Slices A and C) may be at least partially explained by variances in the location at which the results were plotted. Variations in the values from Slice B, however, do not appear to be the result of differences in the slice location.

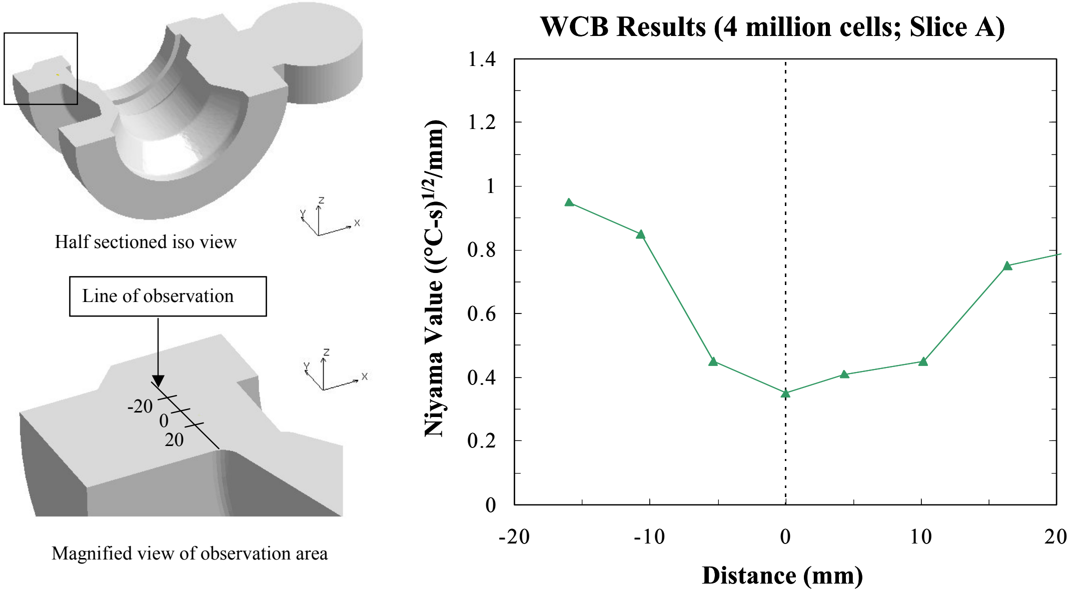


Figure 11. Niyama variation in Slice A along a line of observation in the XY plane

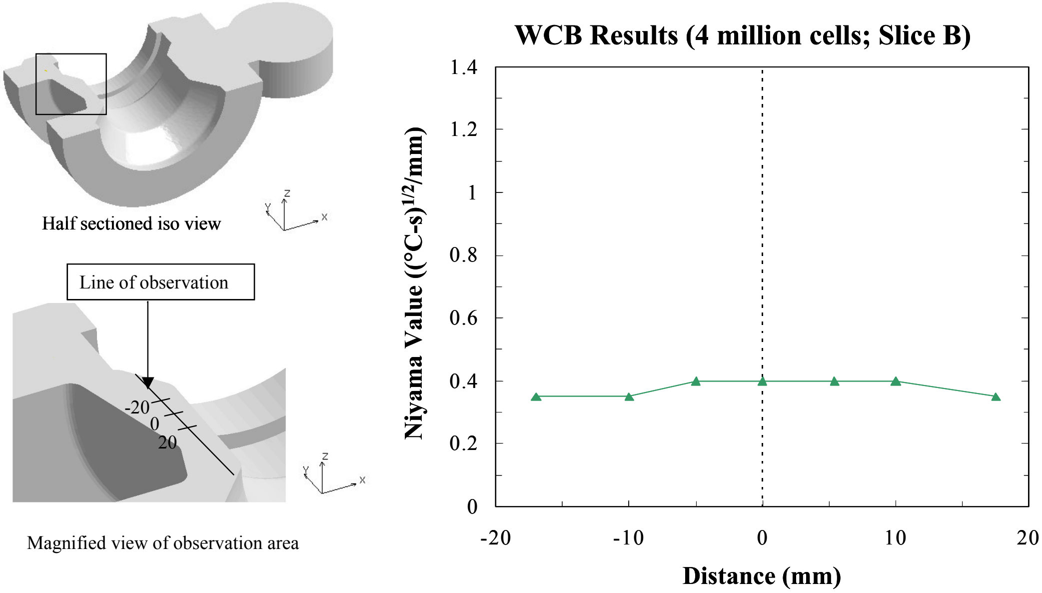


Figure 12. Niyama variation in Slice B along a line of observation in the XY plane

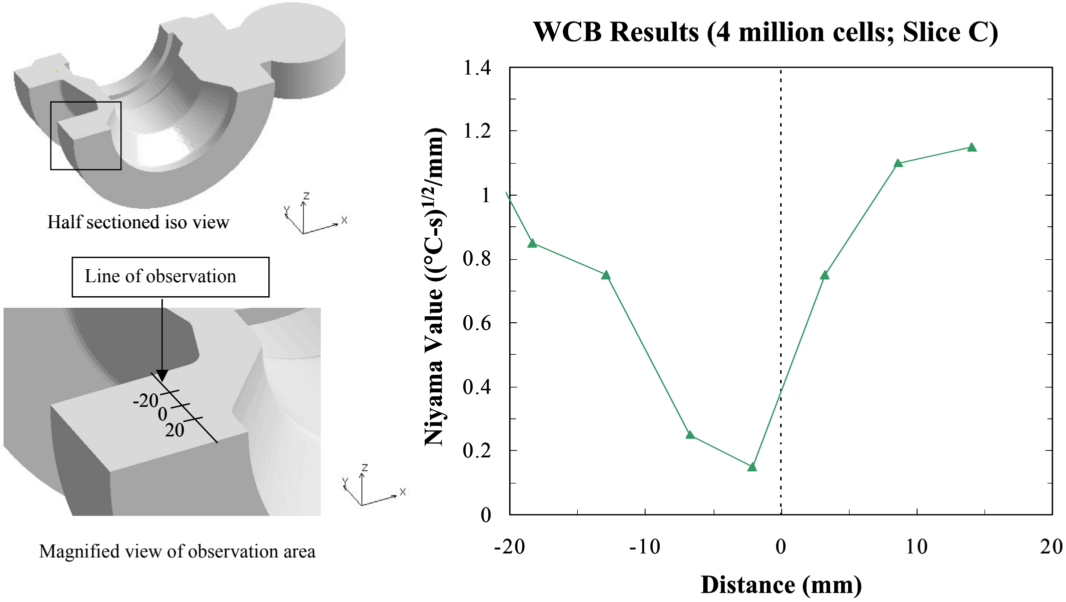


Figure 13. Niyama variation in Slice C along a line of observation in the XY plane

Sensitivity of Niyama Value Predictions to Different Niyama Evaluation Temperatures

Because the cooling rate and temperature gradient at a given location in a casting vary as solidification proceeds, it follows that the Niyama value (which is a function both cooling rate and temperature gradient) varies during solidification as well. Due to this, the choice of temperature at which the Niyama criterion is evaluated may affect the resulting values. This is investigated in the present sensitivity study. Figure 14 indicates Niyama variations along the same line of observation as in figure 10, using 4 million metal cells and evaluating the Niyama criterion at two different temperatures: (1) 10% of the solidification range above the 100% solid temperature (called "90% solid" in the figures below), which is the MagmaSoft default value, and (2) 35% of the solidification range above the 100% solid temperature (called "65% solid"), which is the value recommended by SolidCast. Analogous comparisons were made for Slices B and C as well, but these figures show the same trends seen in figure 14, and as such they are not included here.

To clarify, the simulations represented by the results shown in figure 14 were both performed using MagmaSoft, with all of the simulation parameters identical except for the temperature at which the Niyama criterion is evaluated. The liquidus and 100% solid temperatures for the WCB dataset used in these simulations are 1519°C and 1412°C, respectively (see table 2). This gives a "90% solid" Niyama criterion evaluation temperature of 1423°C, and a "65% solid" temperature of 1449°C. In figure 14, it can be seen that the lowest value along the "90% solid" minimum Niyama curve is smaller than the lowest value along the "65% solid" Niyama curve. Thus, the choice of Niyama evaluation temperature can moderately affect the resulting Niyama values. Since the Niyama value is used to predict shrinkage porosity, the present researchers prefer the "90% solid" temperature, because it is felt that this temperature (near the end of solidification) is representative of when shrinkage porosity is typically forming in castings.

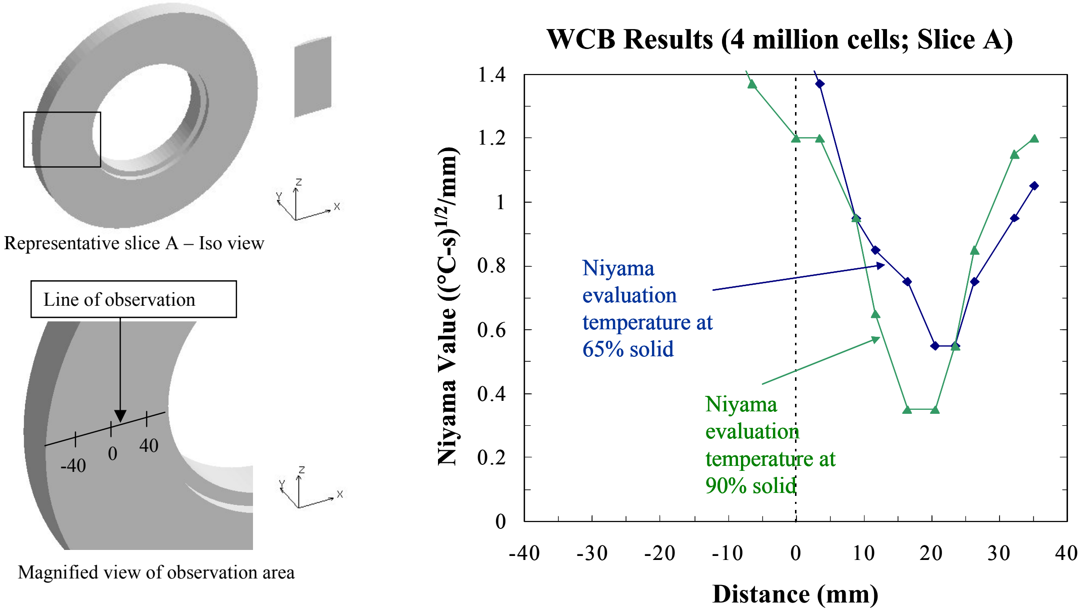


Figure 14. Niyama variation in Slice A along a line of observation in the XZ plane

6. Comparison of Simulation Packages Using the Same Material Property Dataset

Another potential source of variability in the Niyama predictions is differences inherent in the various simulation packages that the user has no control over. This includes different assumptions in the mathematical model and the equations that are implemented in the package, as well as different numerical approximation methods used.

In order to directly compare Niyama predictions from different software packages, one of the SolidCast users from the round robin study was provided with a CF-8M property dataset generated at The University of Iowa. The liquidus and 100% solid temperatures from this temperature-dependent CF-8M property dataset are given in table 2. SolidCast utilizes only constant material properties in its datasets, whereas MagmaSoft uses temperature-dependent properties. To utilize the temperature-dependent CF-8M dataset, the SolidCast user input the latent heat, the liquidus and 100% solid temperatures to define the solidification range, and then selected the 100% solid value of all other material properties, in order to use constant values that are representative of the end of solidification, where shrinkage porosity forms.

Using this common dataset and an initial temperature chosen to give a 100°C superheat (see table 1), the SolidCast user performed another CF-8M solidification simulation of the valve geometry shown in figure 1 (in addition to the one that this user ran for the round robin study, for which the user selected their own material properties and Niyama evaluation temperature). As with the first simulation run by this user, about 4 million metal cells were used in the simulation. For the present simulation, the SolidCast user was asked to use the "90% solid" Niyama evaluation temperature, rather than the "65% solid" value that this user selected for their original simulation. In parallel, the present researchers ran an analogous solidification simulation of the valve geometry with MagmaSoft, using this same CF-8M dataset, superheat value, Niyama criterion evaluation temperature and approximate grid of about 4 million metal cells. Note that this is the same as the simulation that was run by The University of Iowa to produce the results shown in figures 4a and 7, except that this simulation utilized 4 million metal cells to match the number used by the SolidCast user in this study, rather than the 2 million metal cells that were used in the round robin study.

As in the previous cases, the SolidCast user produced results at the three positions shown in figure 2. Detailed discussion with the SolidCast user revealed the exact location of Slices A, B and C (exact y-coordinates of each slice); these slices were not exactly at the middle of the flanges and the valve body, but since the y-coordinates were available, the present researchers were able to produce Niyama plots at the same slice locations selected by the SolidCast user. Using the same procedure as in the minimum Niyama value comparison section, the minimum Niyama value for each slice was read along a line of observation located mid-height of the valve and converted to common units ($(°\text{C-s})^{1/2}/\text{mm}$). In this study, the SolidCast user provided the minimum Niyama values to be compared for each slice in addition to the Niyama plots of each slice, so the uncertainty in the values is very small.

Figure 15 shows the variation in the Niyama predictions for these CF-8M simulations. Note that the SolidCast (Original Dataset) values in figure 15 correspond to Result ID 4-S in figure 7. The MagmaSoft (UI Dataset) values in figure 15 differ slightly from the UI values in figure 7 because the slice locations in figure 15 were chosen to match those of the SolidCast user, rather than being taken at the center of the flanges and valve body (as they were for figure 7). Figure 15 clearly shows that it is possible to obtain very similar Niyama predictions using two different simulation packages (i.e., SolidCast and MagmaSoft). This is true despite the fact that the two packages are based on different model assumptions (e.g., constant versus temperature dependent properties) and numerical approximations and that the sand properties and the heat transfer coefficients used in the two simulations were likely somewhat different.

The comparison between the two SolidCast results in figure 15 underscores the importance of the material property dataset and the Niyama evaluation temperature. The only differences between the two SolidCast results are the CF-8M dataset used and the choice of Niyama criterion evaluation temperature. Very different minimum Niyama values are obtained.

7. Conclusions and Recommendations

The present round robin study showed a large variability in the Niyama values reported by the various foundries. The Niyama values varied not only between different simulation packages, but sometimes also among foundries using the same simulation package. However, a more detailed examination of the results and the present sensitivity studies revealed that virtually all of the variability can be attributed to factors that are under the control of the user of the simulation package. The main factor responsible for differences in the Niyama predictions was found to be the steel property dataset used. Less important factors include the Niyama evaluation temperature, the numerical grid, and mold properties and heat transfer coefficients. Furthermore, the Niyama values varied because some foundries did not provide the contour plots at the requested location in the casting or used an inappropriate scale.

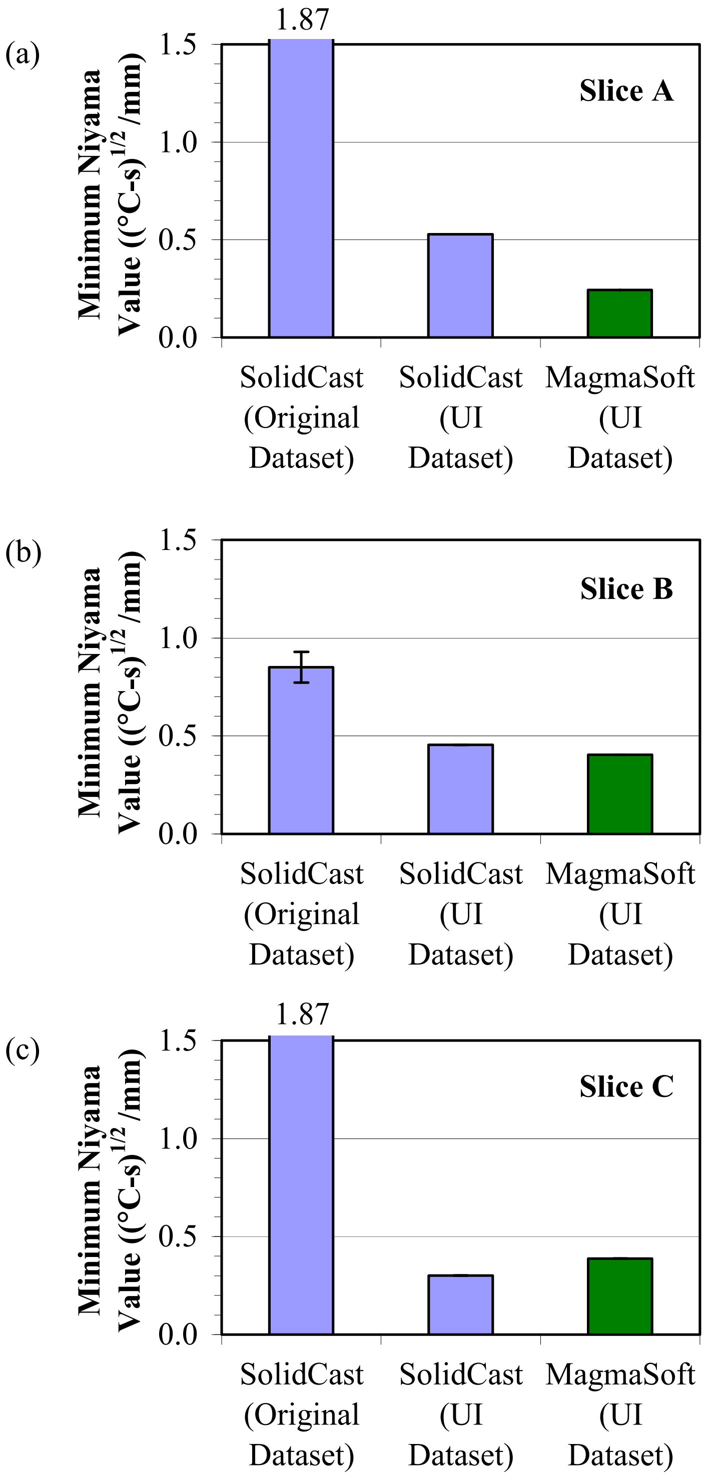


Figure 15. Minimum Niyama values from simulations using a common CF-8M property dataset

Variations in the numerical approximation methods and calculation procedures among different software packages may affect Niyama predictions, but only to a minor degree. This was demonstrated by simulating the valve casting in this study with two different simulation packages using the same steel properties (as far as possible) and Niyama evaluation temperature. Virtually the same minimum Niyama values were predicted.

If a simulation is to be used in a purchase specification, then it is important to ensure that a "good" property dataset is used for the simulation. It would be best if foundries could be supplied with such property datasets for the steels of interest. It must be ensured that the Niyama criterion is evaluated at a specified temperature (e.g., 10% of solidification interval above freezing temperature). To conduct the simulation, the foundry must use reasonably accurate casting process parameters (e.g., pouring temperature, etc.), interfacial heat transfer coefficients and mold properties. It is also essential that the Niyama criterion is reported in agreed-upon units and on specified scales if contour plots are involved. In addition to showing Niyama distributions at various slices of interest in the casting, the foundry should be asked to report minimum Niyama values in critical regions of a casting, rather than at a particular point in space (since the present study detailed how sensitive the minimum Niyama value can be to a particular location). Finally, foundries could also be asked to "qualify" or "benchmark" their simulation and Niyama reporting procedures.

Most casting software packages are capable of simulating the process of filling the mold with liquid metal. However, due to the additional complexities involved, the foundries participating in the present round robin study were asked to not perform a filling simulation. Simulating filling generally results in non-uniform metal and mold temperatures at the beginning of the solidification simulation, but the effect is often small for steel sand castings having large section thicknesses (e.g., more than 1 inch). Nonetheless, additional study may be needed to investigate the sensitivity of Niyama predictions to differences in mold filling simulations.

It should be noted that the critical minimum Niyama value below which shrinkage porosity forms is currently not known for all grades of steel; the reader is referred to references [1-9] for previous research on establishing such critical Niyama values. Also, the Niyama criterion is merely a simple thermal criterion; as such, it can sometimes break down. That is, even if low Niyama values are predicted, a casting section can be shrinkage porosity free. For example, in lateral feeding, there is always a point in the casting between two risers where the temperature gradient becomes zero, thus giving a Niyama value of zero. Finally, it should be kept in mind that there are defects other than shrinkage that can cause a casting to be of less than the desired quality.

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