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DEVELOPMENT OF A METHODOLOGY TO PREDICT AND PREVENT LEAKS CAUSED BY MICROPOROSITY IN STEEL CASTINGS

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ABSTRACT

Present SFSA risering rules [1] were intended to produce steel castings that are free from macroporosity (i.e., shrinkage porosity large enough to be detectable by radiographic testing). No risering rules currently exist to produce castings free from microporosity, however, and microporosity is known to cause leaks in fluid-containing steel castings such as valves. Previous work by the current authors [2] indicates that there is a definite relationship between the occurrence of macroporosity and a local thermal criterion during solidification called the Niyama criterion. The Niyama criterion is defined as $Ny = G/\sqrt{\dot{T}}$, where G is the temperature gradient in K/mm, and $\dot{T}$ is the cooling rate in K/s. Both quantities are evaluated near the end of solidification. It has been determined that if $Ny_{min} > 0.1$, the casting will be radiographically sound (i.e., no macroporosity) [2], assuming the radiographs are produced according to ASTM E94, the Standard Guide for Radiographic Testing [3]. Because the Niyama criterion can predict both micro- and macroporosity, it is suspected that some larger value of Ny_{min} may serve as a threshold for the occurrence of microporosity sufficient to cause leaks, just as 0.1 serves as a threshold for macroporosity. To validate this idea, several case studies involving production steel castings, both with and without leaks, were examined. The results of these case studies, presented here, support the idea of a larger threshold minimum Niyama value (on the order of 0.5 – 1) for microporosity.

INTRODUCTION

Leaks in fluid-containing steel castings (e.g. valves) are a major cause of casting rejection or rework. Because leaks are often caused by microporosity, they are frequently combated through the use of additional risers and/or chills. Such procedures lower the casting yield and increase rigging cost. Often, leaks are only detected after machining operations, which further increases the cost. Present risering rules [1] are mainly intended to prevent centerline macroporosity detectable by radiographic testing. Microporosity is not detectable by standard radiographic or ultrasonic testing. Little is known about proper risering procedures to prevent microporosity. Generally, more risers or chills are needed to prevent microporosity than to prevent macroporosity. If available rules for preventing macroporosity are used as the only means to perform riser design, microporosity, and hence leaks, may result.

Previous work by the current authors [2] indicates that there is a definite relationship between the occurrence of macroporosity and a local thermal criterion that can be evaluated during solidification called the Niyama criterion. The Niyama criterion, which is calculated by many software packages that simulate the casting solidification process, is defined as $Ny = G/\sqrt{\dot{T}}$, where G is the temperature gradient and $\dot{T}$ is the cooling rate. Both quantities are evaluated near the end of solidification. The Niyama values discussed in this work are computed with G in K/mm and $\dot{T}$ in K/s, giving Ny in $(K\ s)^{1/2}/mm$. It has been determined that if $Ny_{min} > 0.1$, the casting will be radiographically sound (i.e., no macroporosity) [2], assuming the radiographs are produced according to ASTM E94, the Standard Guide for Radiographic Testing [3]. It is important to note that the value of Ny computed by simulation packages can vary from one package to the next, because each software package computes Ny under slightly different conditions. For example, one package may evaluate Ny at the solidus temperature, and another may evaluate it at a temperature slightly above the solidus temperature. The sensitivity of the Niyama criterion to different calculation parameters is discussed in the Appendix. The threshold value of $Ny_{min} = 0.1\ (K\ s)^{1/2}/mm$ stated above was determined using the default Niyama criterion calculation parameters utilized by the simulation package MAGMAsoft. See the Appendix for details.

Because the Niyama criterion can predict both micro- and macroporosity, it is suspected that some larger value of Ny_{min} may serve as a threshold for the occurrence of microporosity sufficient to cause leaks, just as 0.1 serves as a threshold for macroporosity. To validate this idea, the present work discusses three case studies involving production steel castings that had problems with leaks. In each case, the casting foundry changed the rigging and solved the leaking problem. Both the original (when leaks occurred) and revised (when the problem was solved) riggings were simulated using MAGMAsoft for each case study, and the Niyama values in the area where the leaks originally occurred were investigated. By comparing the Niyama values when leaks occurred with the values after the problem was removed, it is possible to get an idea of what the threshold minimum Niyama value is for leaks of this nature. This is the objective of the present study.

CASE STUDY #1: ELBOW CASTING

The first case study concerns WCB steel elbow castings produced in a shell sand mold. Two views of the casting are shown in Figure 1. After machining, about 10% of these elbow castings had shrinkage defects on the flange face, where the riser contact had been (see Figures 1(a) and 2(b)). Some of the defects were visible, while others were found by the leaks they caused during pressure testing. Radiographs taken of the flange showed clearly visible shrinkage defects in some of the castings.

The problem was solved by altering the gating and risering designs. The original rigging is shown in Figure 2, and the revised rigging is given in Figure 3. By comparing these figures, it is seen that the diameters of the downsprue and the central riser that feeds both elbows were increased. Also, the gating from the inlet was altered so that two runners come out of the downsprue, instead of having one runner branch off of the other one (as in the original design, shown in Figure 2(b)). Finally, an extra runner was added, between the central riser and the riser connected to the flange face of the elbow casting on the

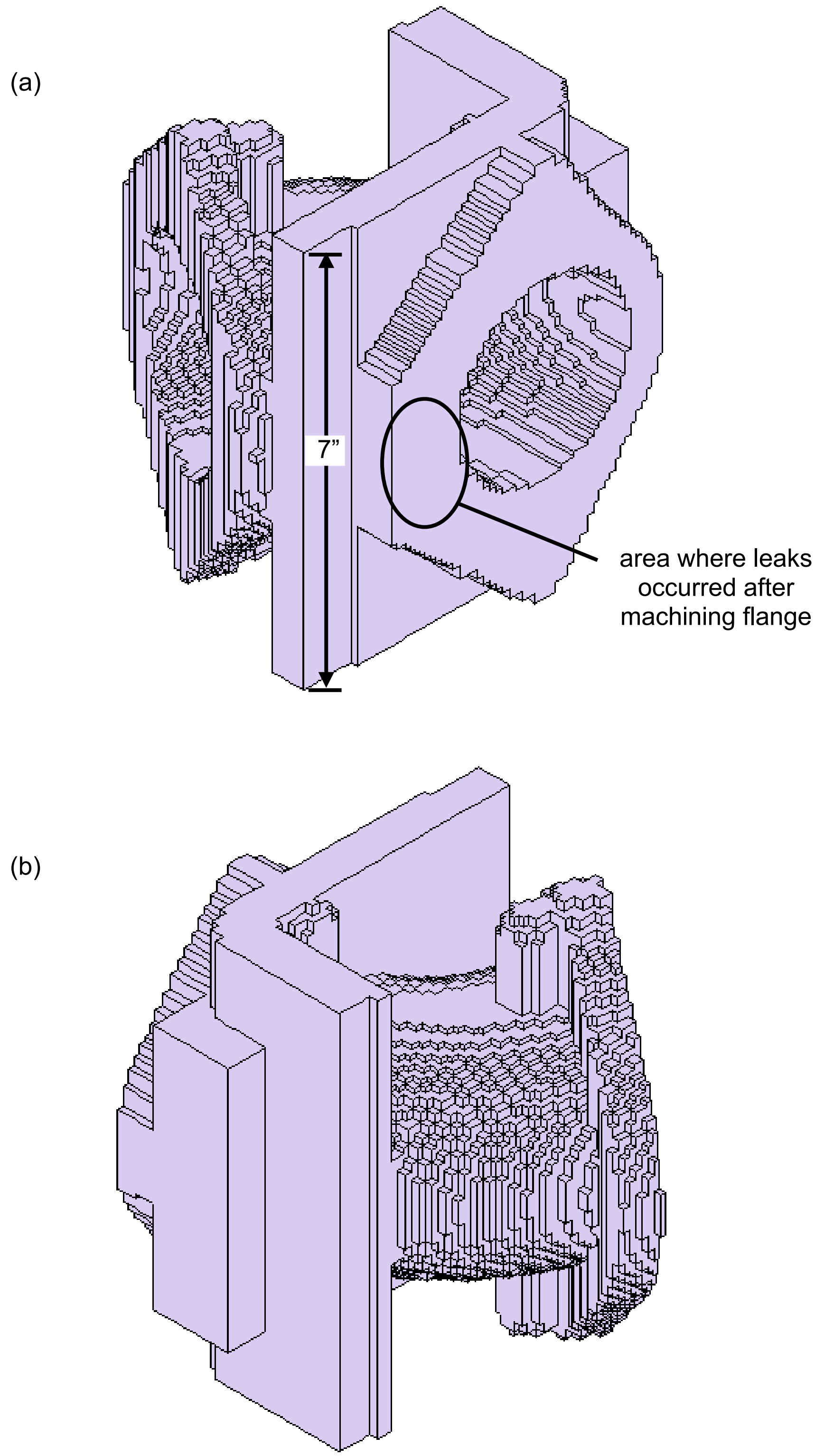

Figure 1 Two views of the elbow casting.

(a)

(b)

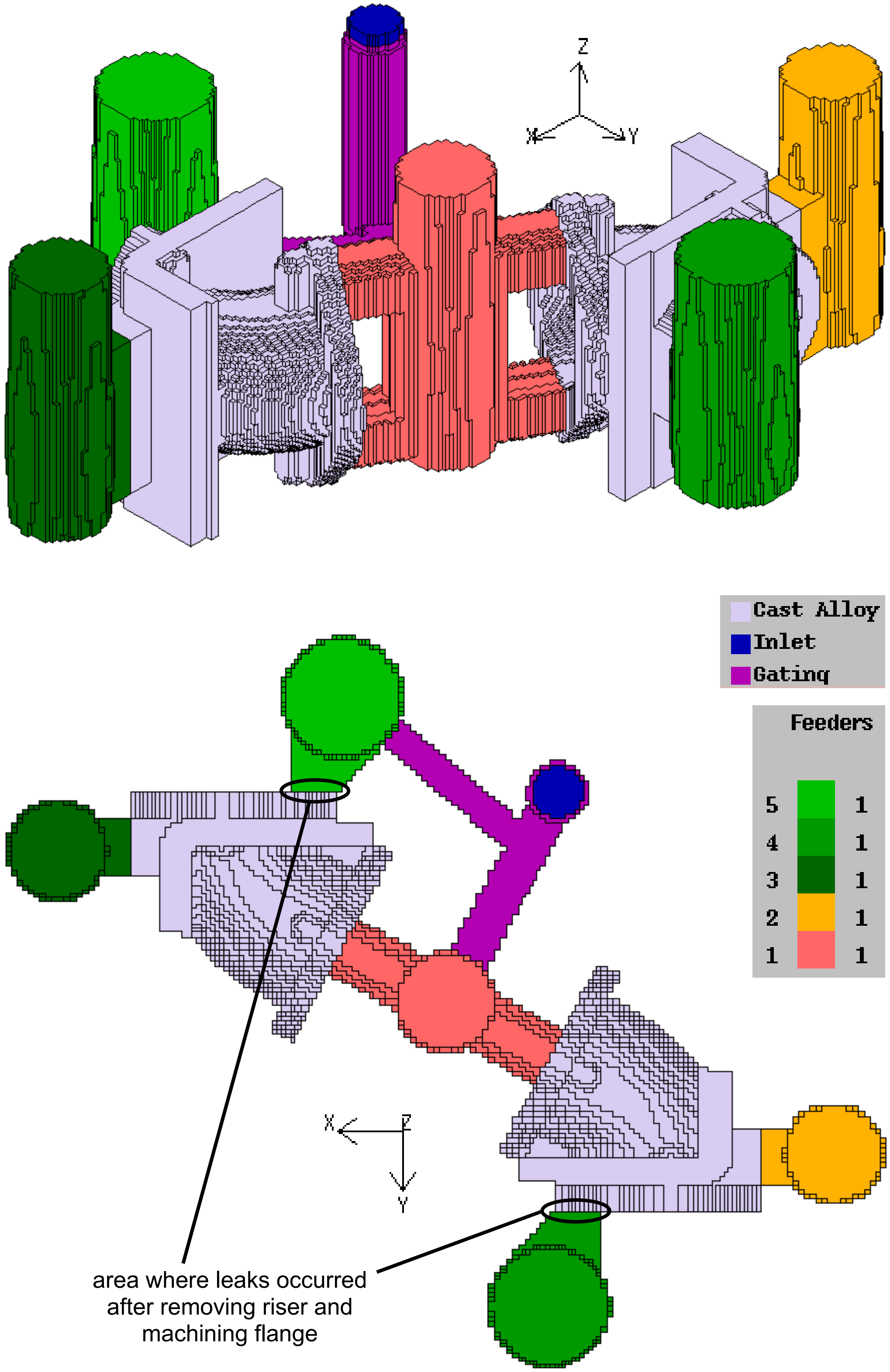

Figure 2 (a) Isometric view of the simulated original rigging, and (b) top view of the original rigging, indicating where the leaks occurred.

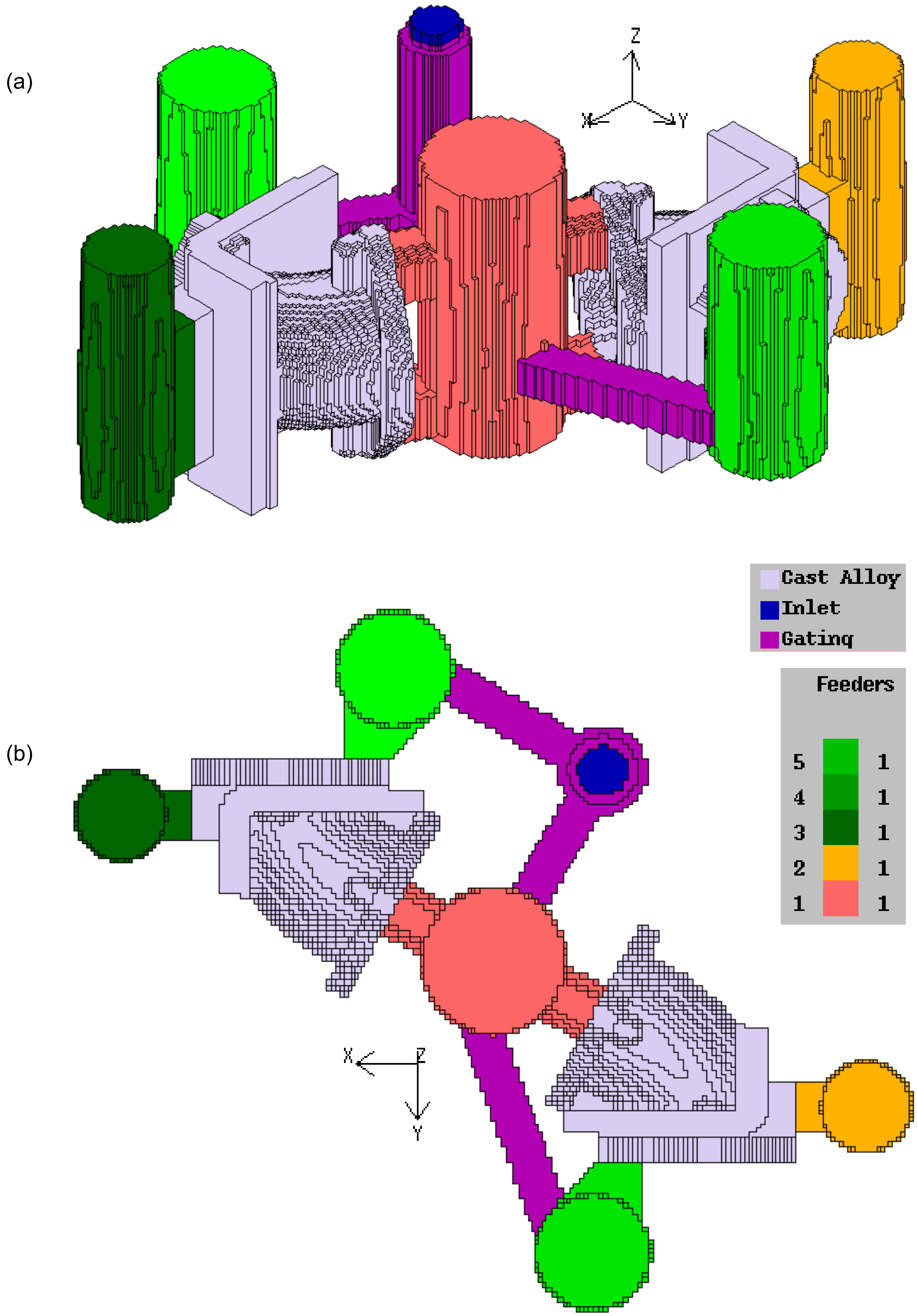

Figure 3 (a) Isometric view and (b) top view of the revised rigging.

right side of Figure 3. Once these changes were made in the rigging, the flange faces of the elbow castings were radiographically sound and no longer leaked.

This leaking problem was examined by simulating the casting process using MAGMAsoft. WCB steel was modeled using WCB steel data (C19Mn5) from MAGMA's database, and the shell sand mold was simulated with MAGMA's dry silica sand. As shown in Figures 2 and 3, two elbows are cast in each mold box. A central riser feeds both elbows, and then there are two additional risers for each elbow. As mentioned above, the riser contact on each elbow where the defects were found is circled in Figure 2(b).

After the casting process was simulated, the Niyama values were investigated. The Niyama values in the area where the leaks occurred in the original rigging are shown in Figure 4. The left side of Figure 4 shows a cross-section indicating the Niyama values where the problems occurred, while the right side contains close-ups of the Niyama values for the z-layers (i.e., x-y planes) in the immediate vicinity of the problem area. The flange shown in Figure 4 contains 7 y-layers (i.e., x-z planes) of computational elements. Approximately 25% of the thickness of the flange face was removed during machining, which corresponds to removing about 1.5 y-layers of computational cells from the flange face. Therefore, the Niyama values of the first y-layer of computational cells on the flange face (i.e., the layer of cells touching the riser contact) are ignored, since that material is machined away. The lowest Niyama values in the next few y-layers of the flange are indicated on the close-ups of the problem area on the right side of Figure 4. It is seen that the minimum Niyama value in the second and third y-layers from the riser contact (i.e., in the region where the machined flange face will be) is about 1.2.

The corresponding Niyama plots for the revised rigging shown in Figure 3 are given in Figure 5. By comparing Figure 5 to Figure 4, it is seen that there are significantly fewer low-Niyama indications (i.e., darker colors) in the flange with the revised rigging than with the original rigging. Figure 5 indicates that the minimum Niyama value in the second and third y-layers from the riser contact is about 1.5 – 1.7. It should be mentioned that the Niyama values shown in Figures 4 and 5 are for the elbow on the right side of Figures 2 and 3, respectively. The left elbow casting was investigated in the same manner, and the Niyama plots are qualitatively very similar to those shown in Figures 4 and 5. The minimum Niyama value for the left elbow in the original rigging is about 1.2 – 1.4. The minimum Niyama value for the left elbow in the revised rigging is about 1.3 – 1.6. As was found for the right elbow casting, the revised rigging significantly reduces the number of low-Niyama indications in the area of interest in the left elbow casting as well. The results for the left elbow can be seen in [4].

It should be noted that these minimum Niyama values seem high, according to the Niyama threshold stated in the introduction of this paper (no macroporosity if $Ny_{min} > 0.1$). Because macroporosity or leaks were only found in 10% of these castings, one would not necessarily assume that the minimum Niyama value should be less than 0.1, but it seems that it should be closer to 0.1 than to 1.0. This discrepancy between simulation and reality could be the result of several factors. First of all, the actual casting parameters (e.g., pouring temperature, pouring time) could be somewhat different than the values used in the simulations. Secondly, the use of more accurate mold properties in the simulation could change the simulation results. Finally, the thermal boundary conditions for this problem are difficult to model. Large fans and dust collectors provided rapid air movement around the molds during casting, and this was not accounted for in the simulation. Normally, airflow around the outside of a mold makes little difference in the simulation results. In this case, however, the mold wall was only about 0.5 inches thick. Thus, inaccurate modeling of the thermal boundary conditions may have influenced the final results.

These last two possibilities were investigated by performing two additional simulations with the original rigging. First of all, the original casting process was re-simulated using MAGMA's shell sand to model the mold material, instead of dry silica sand. This lowered the minimum Niyama value in the leaking region to about 0.74 – 0.84. Then, the heat transfer coefficient between the metal and the mold was increased from 1000 W/m-°C to 1200 W/m-°C (again using MAGMA's shell sand), to determine if accounting for increased mold surface heat transfer would further lower the Niyama values. The minimum Niyama value for this simulation dropped to about 0.57 – 0.77, indicating that accounting for additional surface heat transfer does, in fact, result in lower Niyama values. Figure 6 shows the results of this simulation for the

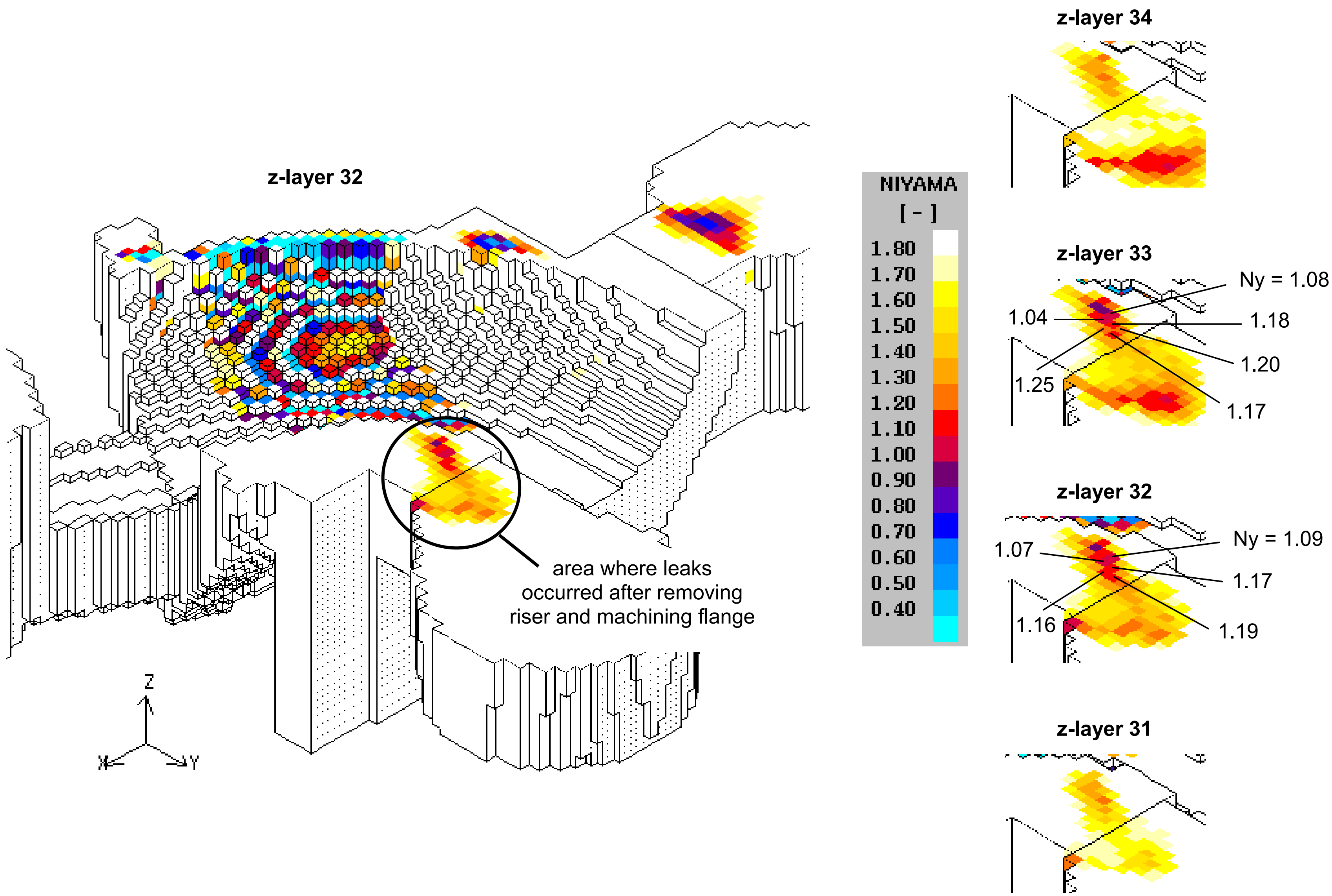

Figure 4 Niyama values for the right elbow (on the right side of Figure 2(a)), simulated with the original rigging.

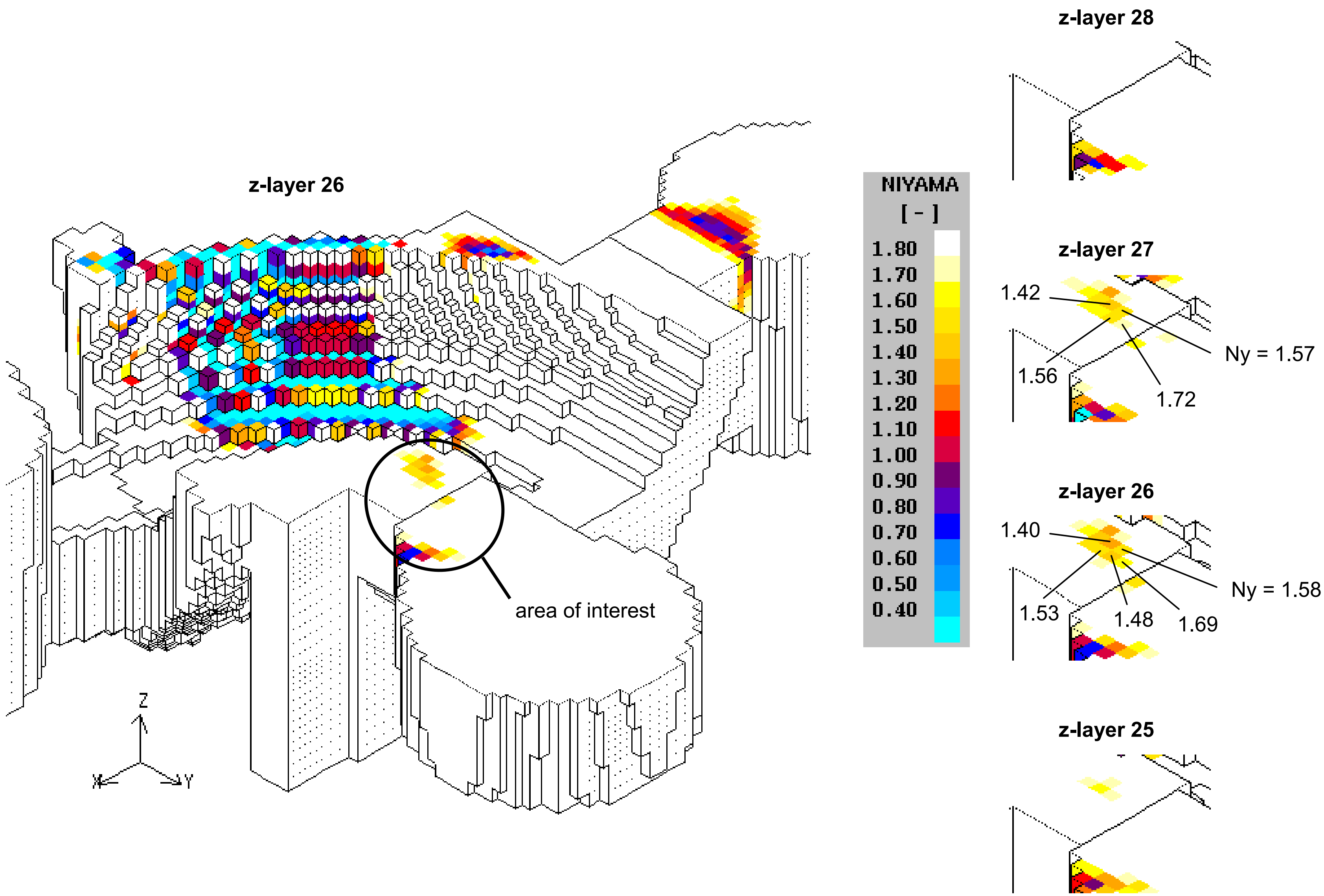

Figure 5 Niyama values for the right elbow (on the right side of Figure 3(a)), simulated with the revised rigging.

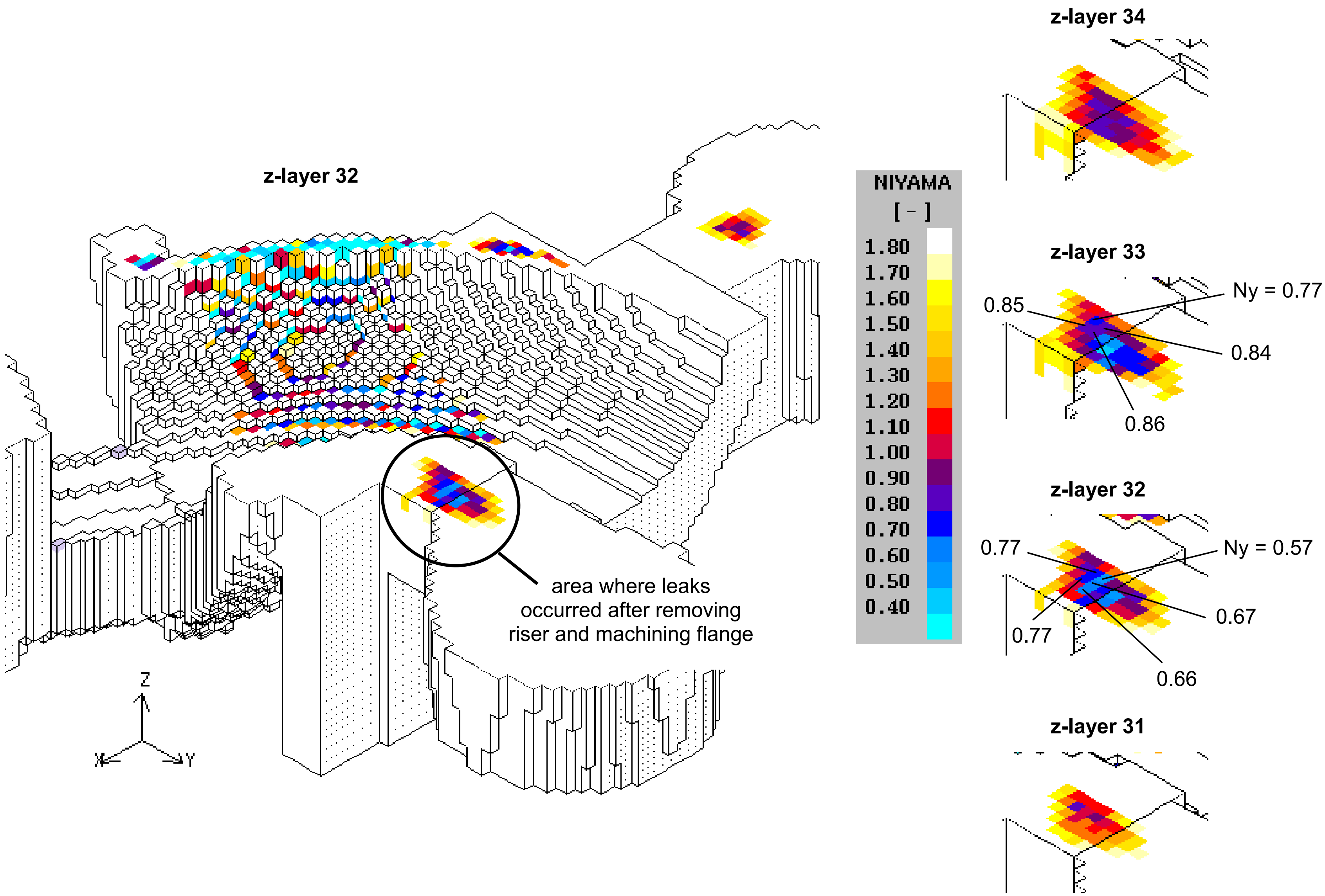

Figure 6 Niyama values for the right elbow (on the right side of Figure 2(a)) simulated with the original rigging, but with shell sand and a higher heat transfer coefficient between the metal and the mold.

right elbow. Clearly, the Niyama values are significantly lower than in the original simulation (see Figure 4), indicating better agreement with the actual casting results.

In summary, the simulation of the revised rigging shows that the minimum Niyama values in the area where leaks were occurring are somewhat higher (1.3 – 1.7) than the corresponding values from the original rigging (1.2 – 1.4). Also, there are significantly fewer low-Niyama values in the revised rigging. Thus, the simulation results do suggest that more sound castings should result from the revised rigging, which is exactly what was found during the actual casting process. The minimum Niyama values for this study may be a little high, and it was shown that this could be remedied by changing some of the modeling parameters. However, the trend of increasing Niyama values as casting soundness improves is still evident.

CASE STUDY #2: VALVE A

This case study involves overpressure valve castings made of WCB steel in a PUNB mold (see Figure 7). After casting, a larger hole was bored into one of the existing holes in order to fit an overpressure nozzle in that end of the valve. However, when the nozzle was inserted into the hole and the valve was pressure tested, 12% of the valves (11 of 92 cast) leaked around the gasket that was supposed to form a seal around the nozzle. Radiographic examination revealed that some of the valves had visible shrinkage porosity (ASTM Level 1 or 2) in the valve seat; this region is circled in Figure 7(b). The gasket passes through the vicinity of this region.

To solve this problem, the foundry altered the rigging by placing two chills on each valve; one on the flange face and one in the valve seat. The placement of the chills is shown in top-view in Figure 8, which also shows the riser/feeder arrangement for this rigging. The inset in Figure 8(b) shows another view of one valve, to better indicate the location of the chills. Since chills were added, the foundry has cast 584 of these valves, and none of them has leaked.

The solidification process for both the original and revised riggings has been simulated with MAGMAsoft. The MAGMA model of the original rigging is shown in Figure 9. WCB steel was modeled using the WCB steel data (C19Mn5) in the MAGMA database, and MAGMA's furan sand was used to simulate the PUNB mold. Although only two valves are shown in this figure, there were four valves per mold box. However, the rigging was symmetric about the center of the gating system, so only half of the mold box was simulated, using a symmetry boundary condition on the vertical plane passing through the centers of the inlet and the primary runner of the gating system.

A top-view plot of the original rigging Niyama values for the cross-section that runs through the center of the valves is shown for one valve in Figure 10. The Niyama values for both valves are very similar, so results are only shown for one valve. The bold lines in Figure 10 represent the hole after machining. The cross-hatched region of this machined hole indicates the gasket location. This figure shows that there is a relatively low-Niyama region on the edge of the gasket in the valve seat (the same region circled in Figure 7(b)). This figure indicates that, if the leaks are occurring around the gasket, the problem should be evident in x-layer 44, 45 or 46 (i.e., the y-z plane containing the gasket, or one of the planes adjacent to it). The Niyama plots for these three x-layers were investigated, and the lowest Niyama values in the area of interest were found in x-layer 46 (the minimum Niyama values were 0.72 for layer 44, 0.32 for layer 45 and around 0.1 for layer 46). The Niyama plot for x-layer 46 is shown in Figure 11. It is evident from this figure that there are more low-Niyama indications on the side of the hole nearest the valve seat (the right side of the hole). The minimum Niyama value in the region of the gasket is somewhere between 0.04 and 0.14. The uncertainty in this value is due to the difficulty in determining whether the cells with $Ny < 0.1$ are in contact with the gasket, or just very close to it.

As mentioned above, this problem was solved through the use of chills. The MAGMA model for this revised rigging is the same as for the original rigging shown in Figure 9, except for the addition of the chills shown in Figure 8(b). The revised rigging Niyama plot for x-layer 46 is given in Figure 12. This figure indicates that the use of chills increased the soundness in the valve seat region, as evidenced

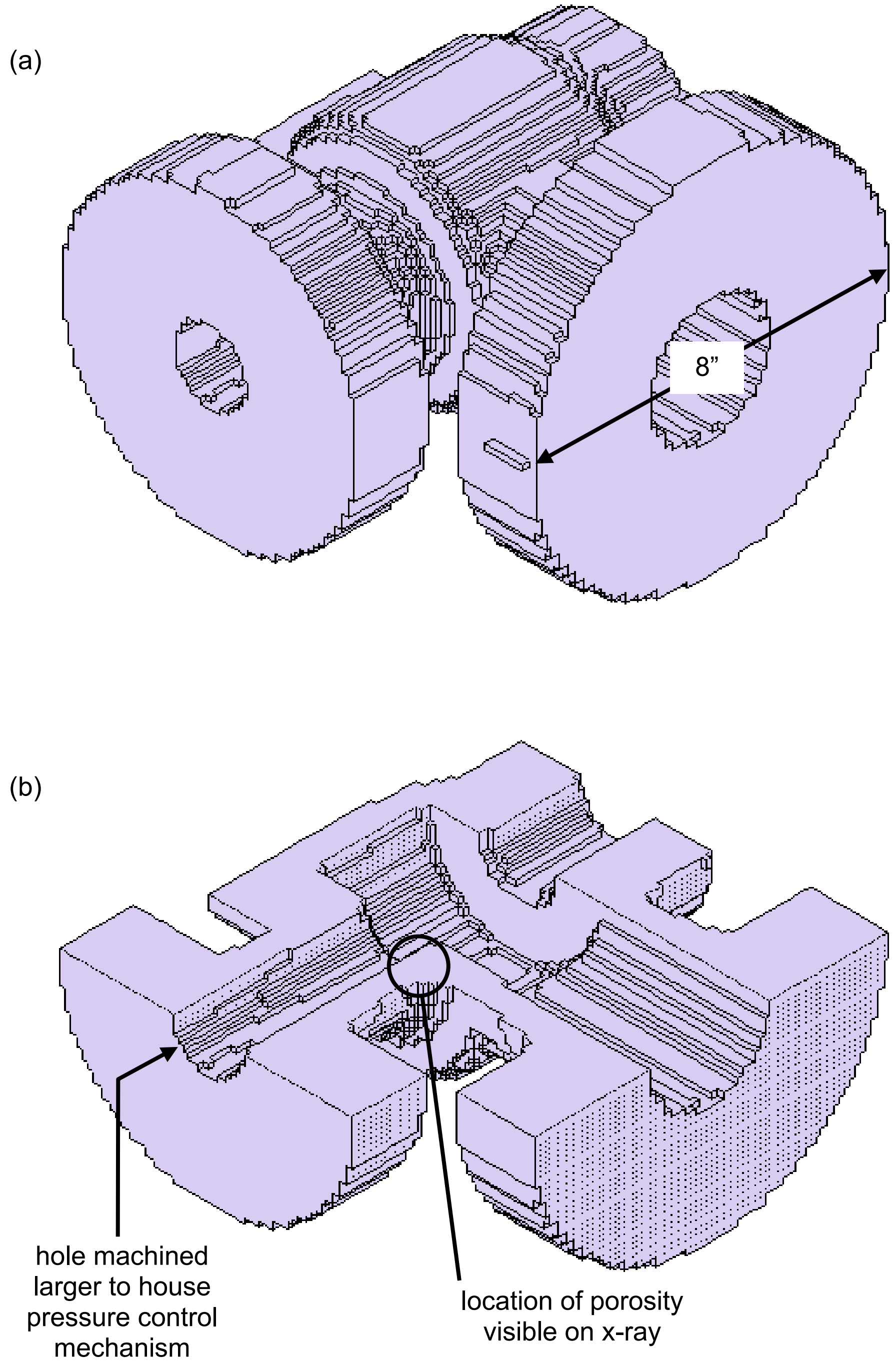

Figure 7 Views showing (a) the overpressure valve, and (b) a cross-section of the valve showing the location of the porosity that causes the leak.

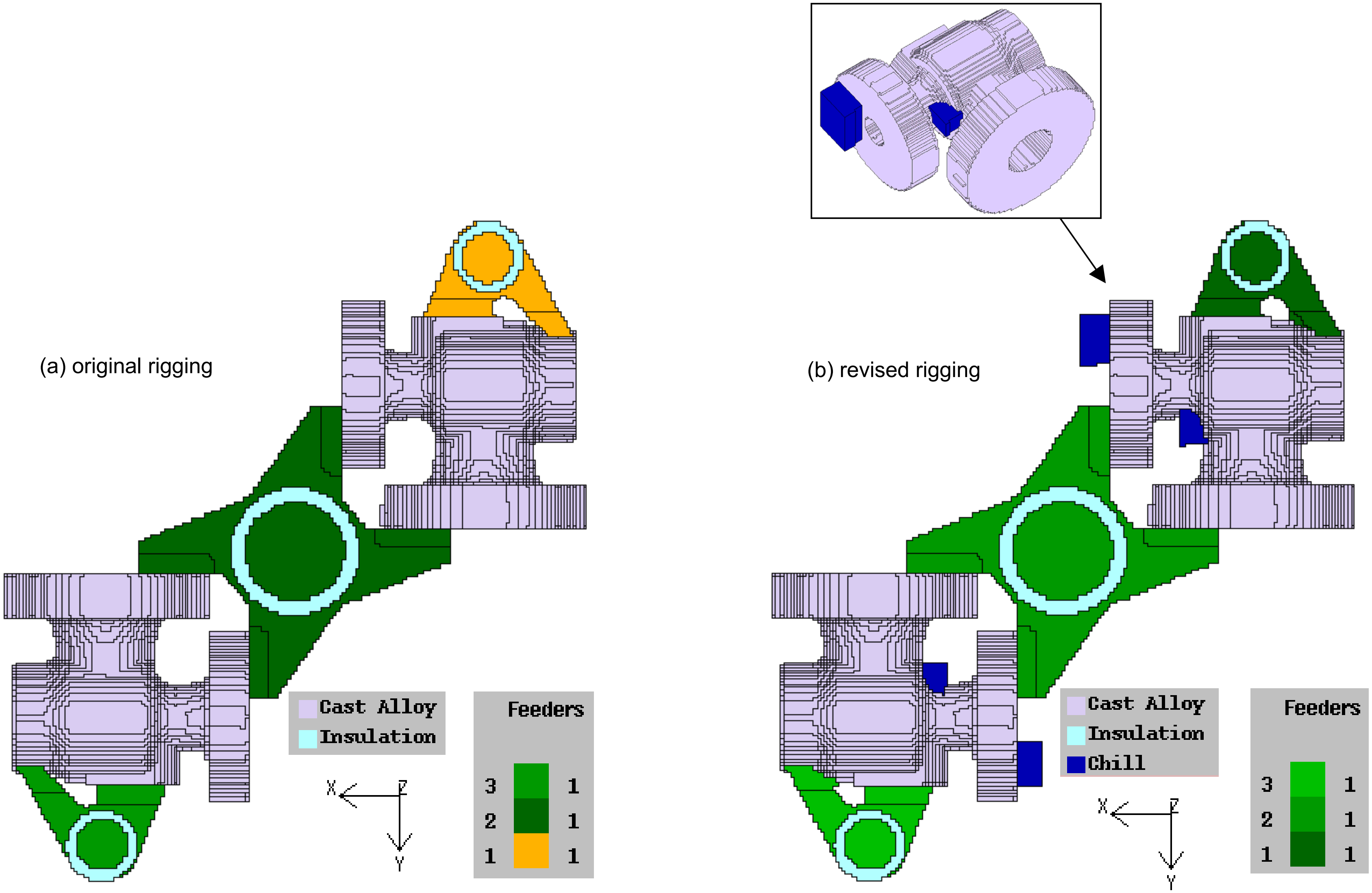

Figure 8 Top view showing (a) the original valve arrangement, and (b) the revised arrangement, with chills.

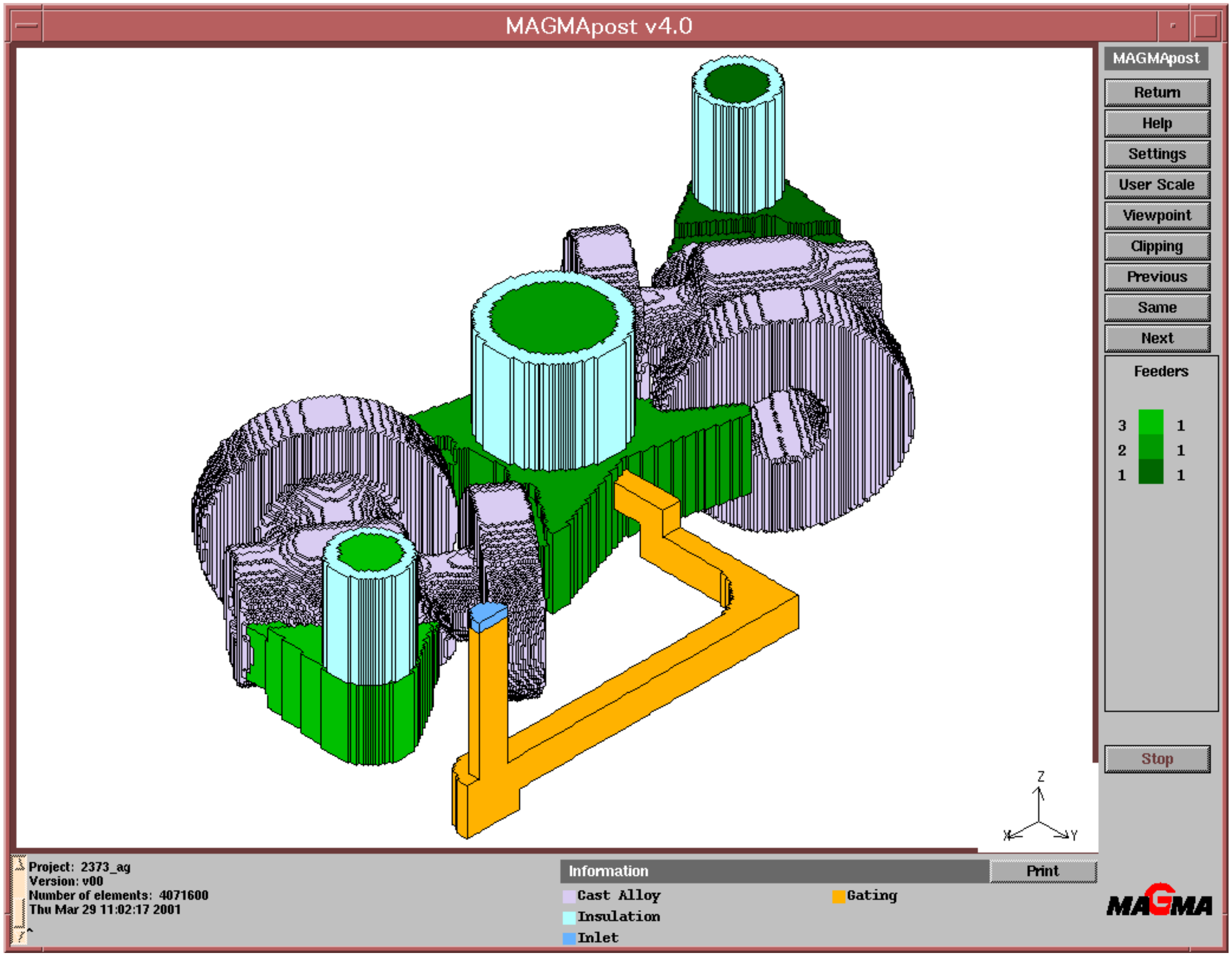

Figure 9 Simulation view of the original rigging for the overpressure valve. Four valves are cast in one mold box; the view shown here is symmetric about the center of the gating system.

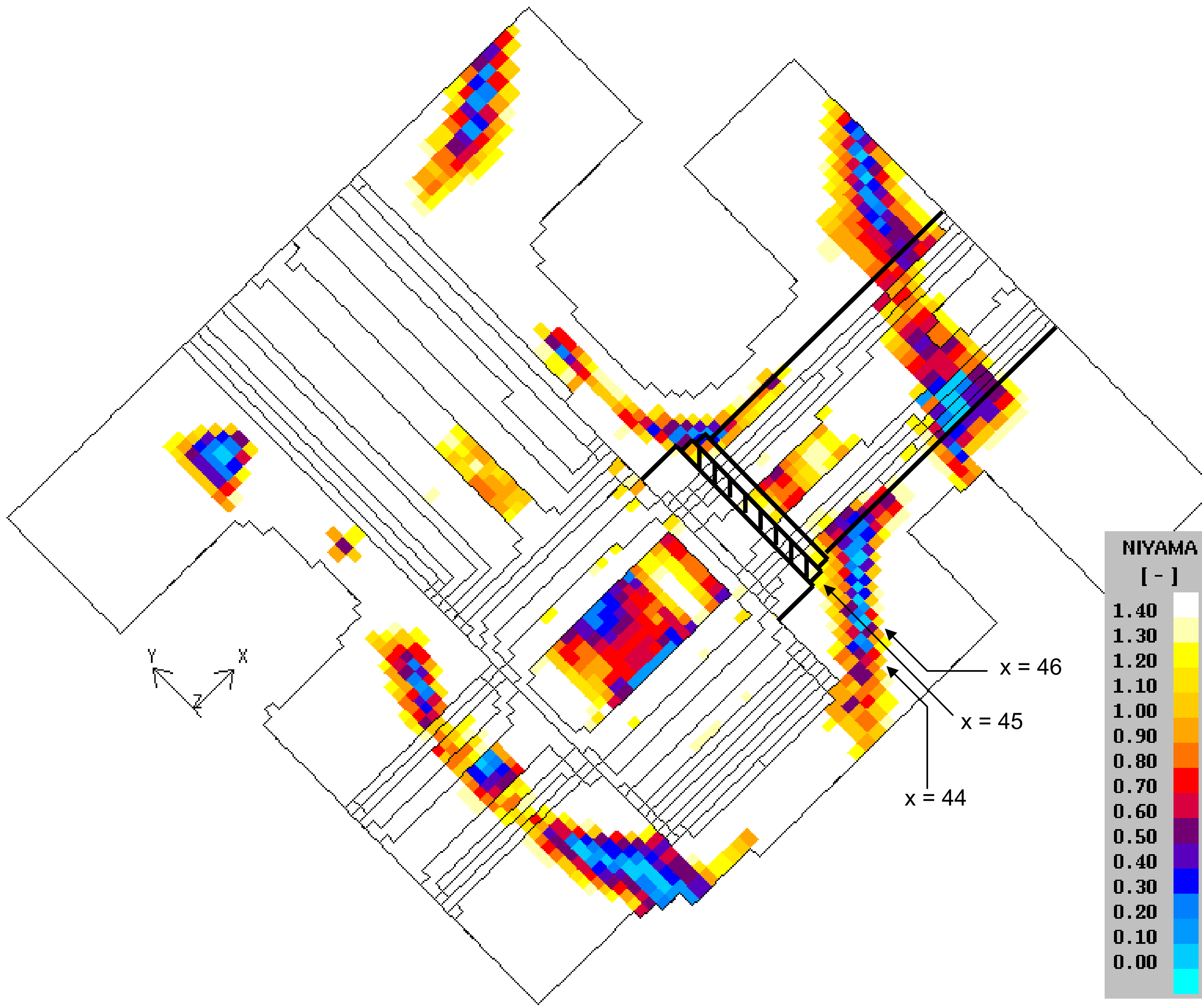

Figure 10 Top view cross-section showing the gasket location (cross-hatched region) and Niyama values for the original rigging.

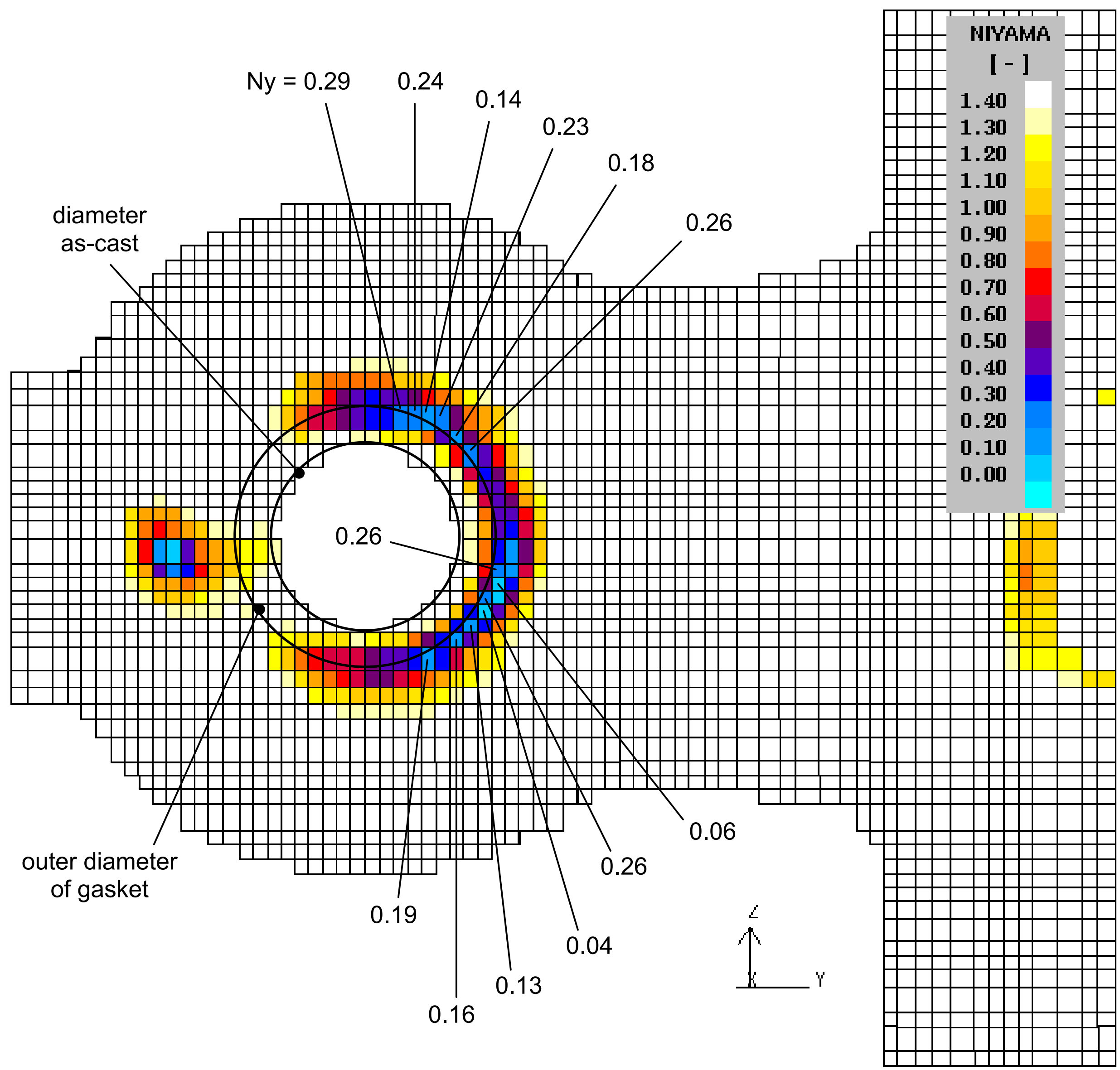

Figure 11 Original rigging Niyama values in the area of the leak for x-layer 46 (see Figure 10 for x-layer definition).

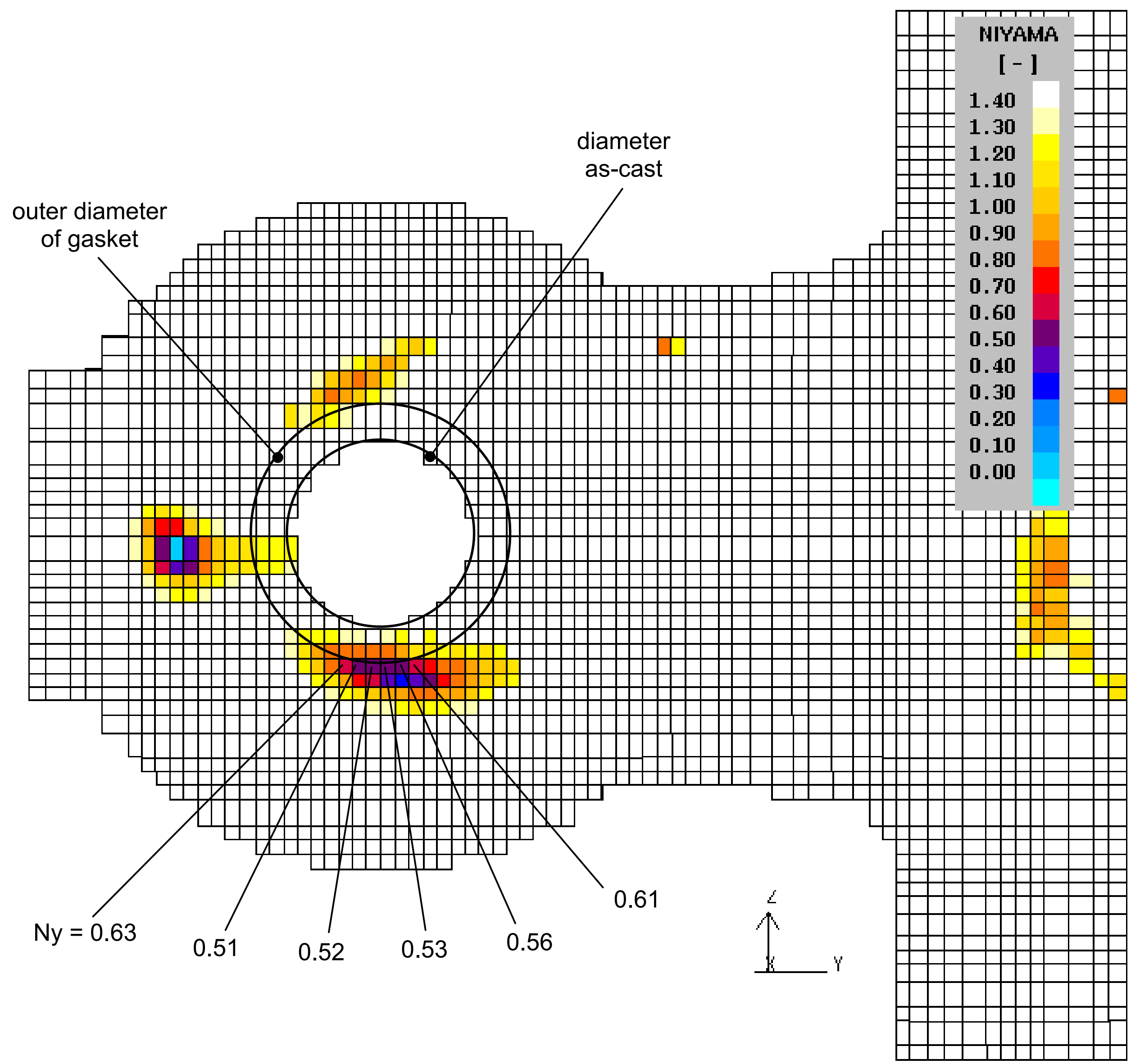

Figure 12 Revised rigging Niyama values for x-layer 46 (see Figure 10 for x-layer definition).

by the lack of low-Niyama indications on the right side of the hole. The minimum Niyama value seen in the region bordering the gasket in Figure 12 is 0.51. The minimum values in x-layers 44 and 45 increased as well. The original and revised rigging Niyama plots for x-layers 44 and 45 are shown in [4].

In summary, simulation of the original casting process indicates that a minimum Niyama value of about 0.1 occurs in the region where the leaks occurred. Due to the presence of macroporosity on x-rays of some of the leaking castings, a minimum Niyama value around 0.1 is to be expected. When chills were added, the minimum Niyama value increased to around 0.5, and leaks no longer occurred.

CASE STUDY #3: VALVE B

This case study involves “baby v-ball” valve body castings made from CG8M steel in a shell mold with silica sand. After machining, the valves were prone to leak around the gasket on the flange face during pressure testing (see Figure 13). It was reported that 2 of 9 valves (22%) from a recent order leaked during pressure testing, and that this was actually an improvement over prior orders. The valves were radiographed, but no shrinkage indications were evident on the resulting x-rays in the area of the leaks. The leaking castings were then sectioned, and photomicrographs were taken of the area where the leaks occurred. Figure 14 shows the microporosity that caused the leak in one of these valves.

In an effort to solve this problem, the casting process was simulated using MAGMAsoft. The simulated rigging is shown in Figure 15. CG8M steel was modeled using the CF8 data given in the MAGMA database (a good match for material properties and chemical composition), and MAGMA’s shell sand was used to simulate the mold. The Niyama values on the flange face that leaked after machining are shown in Figure 16. The minimum Niyama value on the gasket seat appears to be between 0.48 and 0.73, and it occurs in roughly the same location as the leak shown in Figure 13 (i.e., above the machined hole).

Once the low Niyama regions were identified through simulation, changes were made to the rigging to correct this problem. Padding was added in the region between the riser contacts on each side of the valve. This is illustrated in Figures 17(a) and (c), in the top view cross-sections of the original and revised riggings. The front views shown in Figures 17(b) and (d) illustrate that the chill arrangement was also changed, from two separate chills below the valve to a single chill, which was moved further underneath the valve (in the +y direction). Another change evident from Figures 17(b) and (d) is the reshaping of the lower outside (i.e., the side opposite the casting) portion of the risers. This was done on all five risers. Finally, a filter was added at the bottom of the riser through which the metal is poured (the riser with the inlet in Figure 15).

This new rigging was simulated in MAGMA, and the resulting Niyama values are shown in Figure 18. As seen in the figure, the minimum Niyama value in the gasket seat is about 1.4 or higher. Several castings were then produced with this revised rigging. After machining, the castings were radiographed and pressure tested. There were no shrinkage indications on any of the x-rays, and none of the valves leaked in hydro-testing.

In summary, with a minimum Niyama value in the range of 0.5 – 0.7, a significant percentage of these valves had sufficient microporosity to leak around the gasket seat. However, when the rigging was modified to raise the minimum Niyama value in the gasket seat to about 1.4, none of the valves leaked.

FINDINGS AND CONCLUSIONS

In an effort to determine if there is a critical minimum Niyama value above which there will be insufficient microporosity to cause leaks in fluid-containing steel castings, three case studies involving industrial steel castings that had leaking problems were examined. The first case study was an elbow casting that originally leaked around the flange face in about 10% of the castings. The shrinkage that caused the leaks was visible to the naked eye for some of the castings, and found during pressure testing in others. Radiographs taken of the flange showed clearly visible shrinkage defects in some of the castings. The

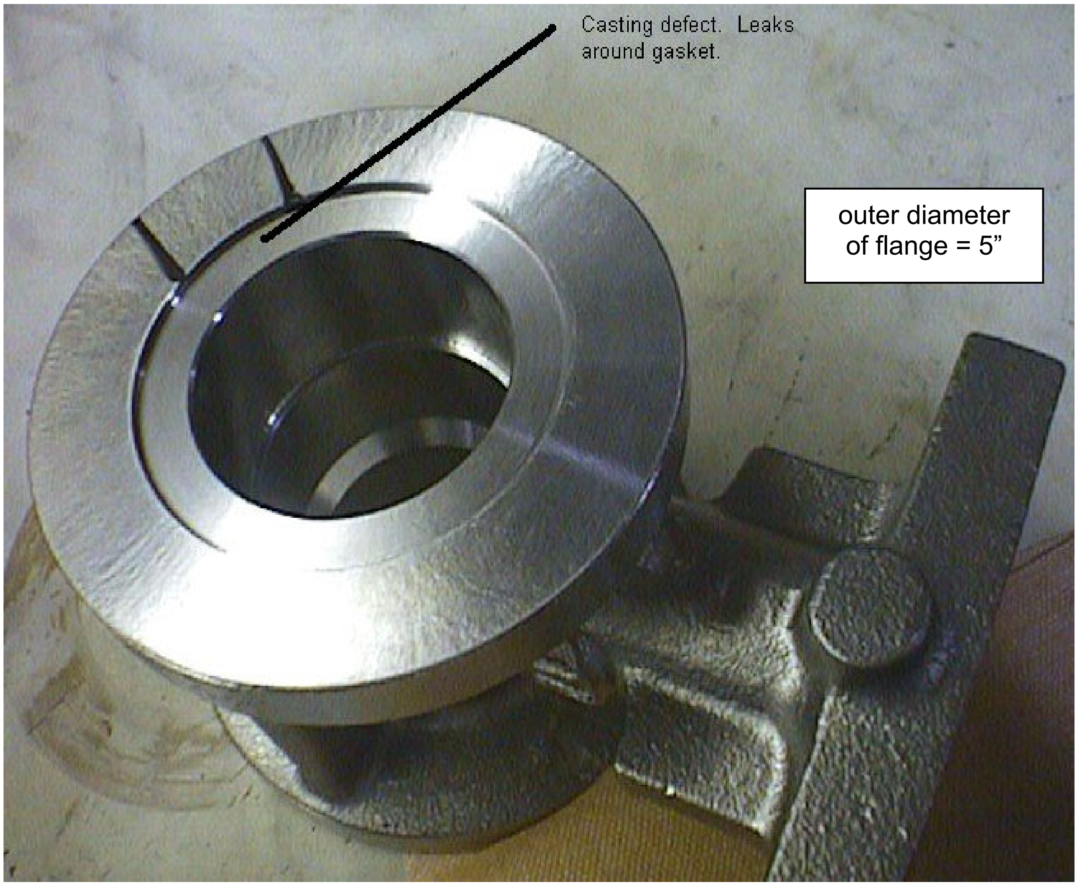

Figure 13 Photo of valve after machining, indicating the location of the leak on the gasket seat.

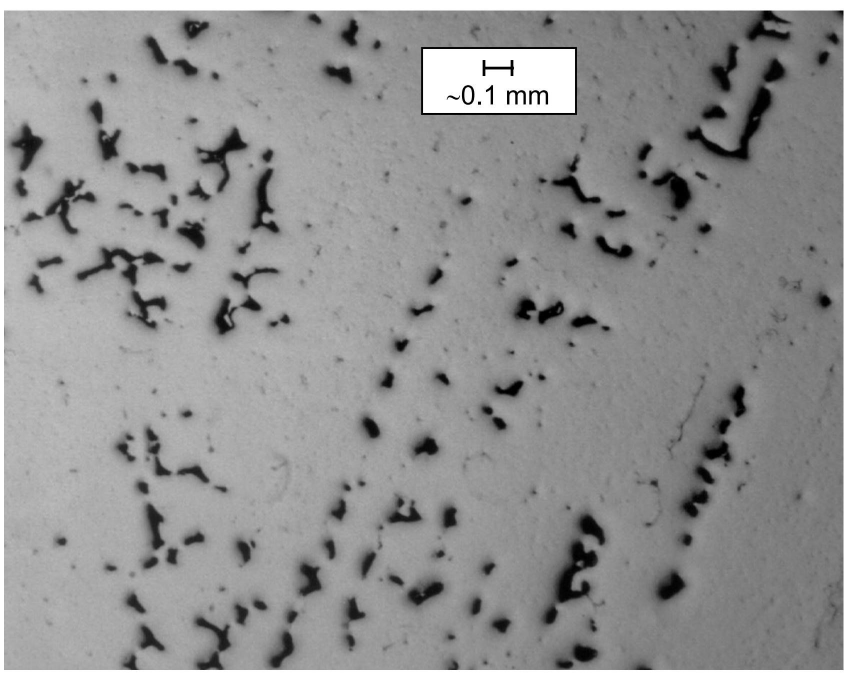

Figure 14 Magnified photomicrograph of microporosity in a leaking valve casting.

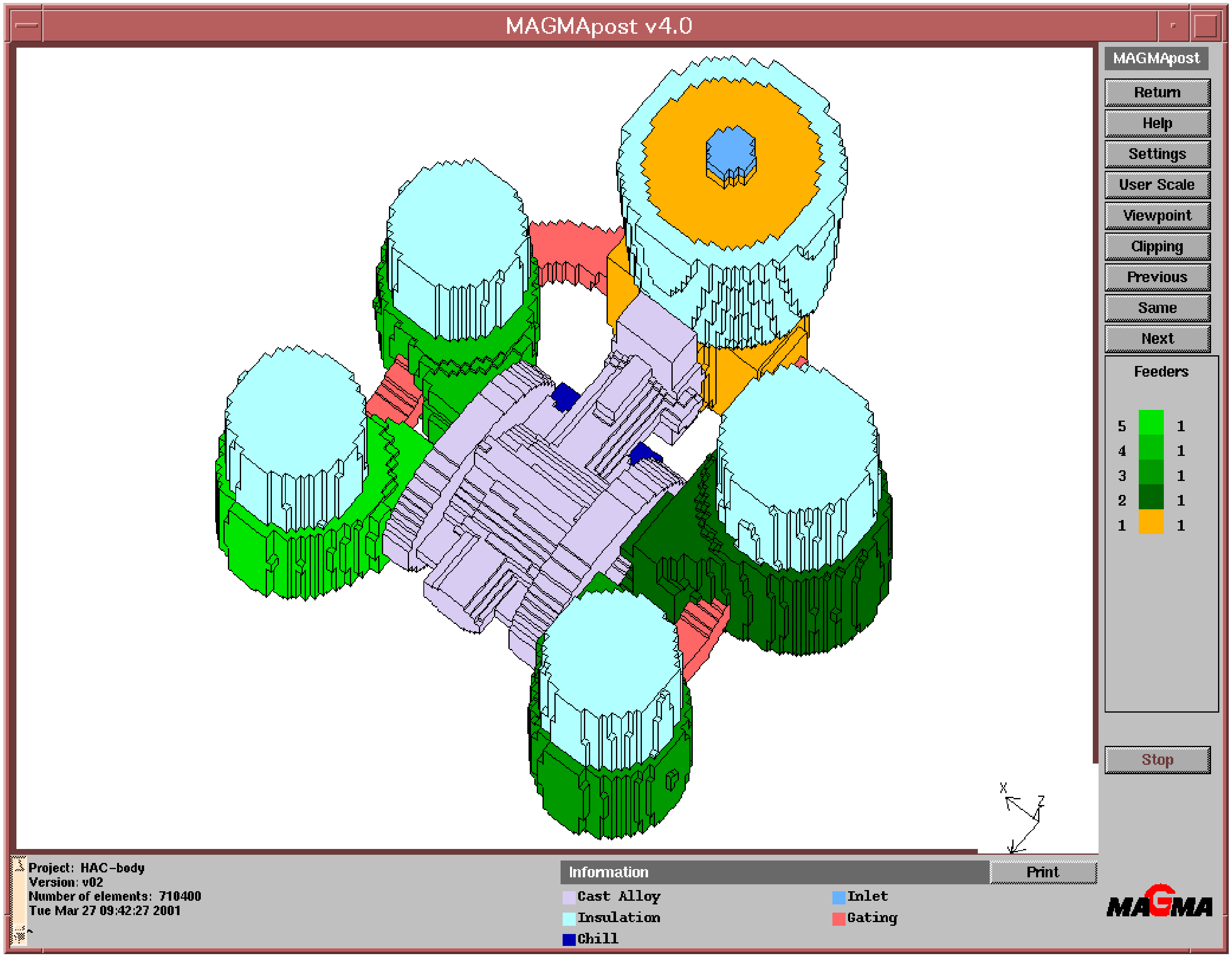

Figure 15 Simulation view of the original rigging for “baby v-ball” valve casting.

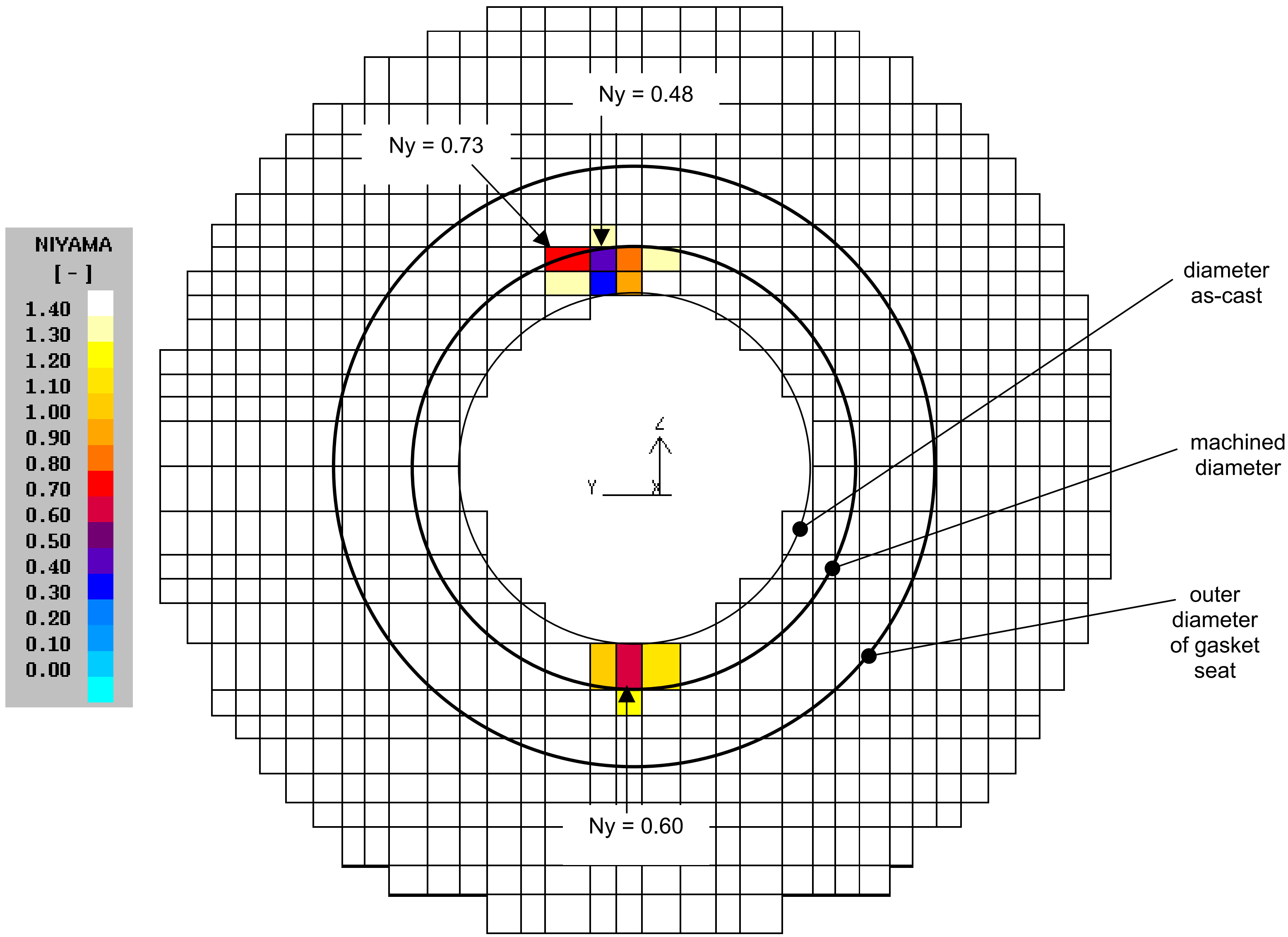

Figure 16 Original rigging Niyama values on the machined flange face.

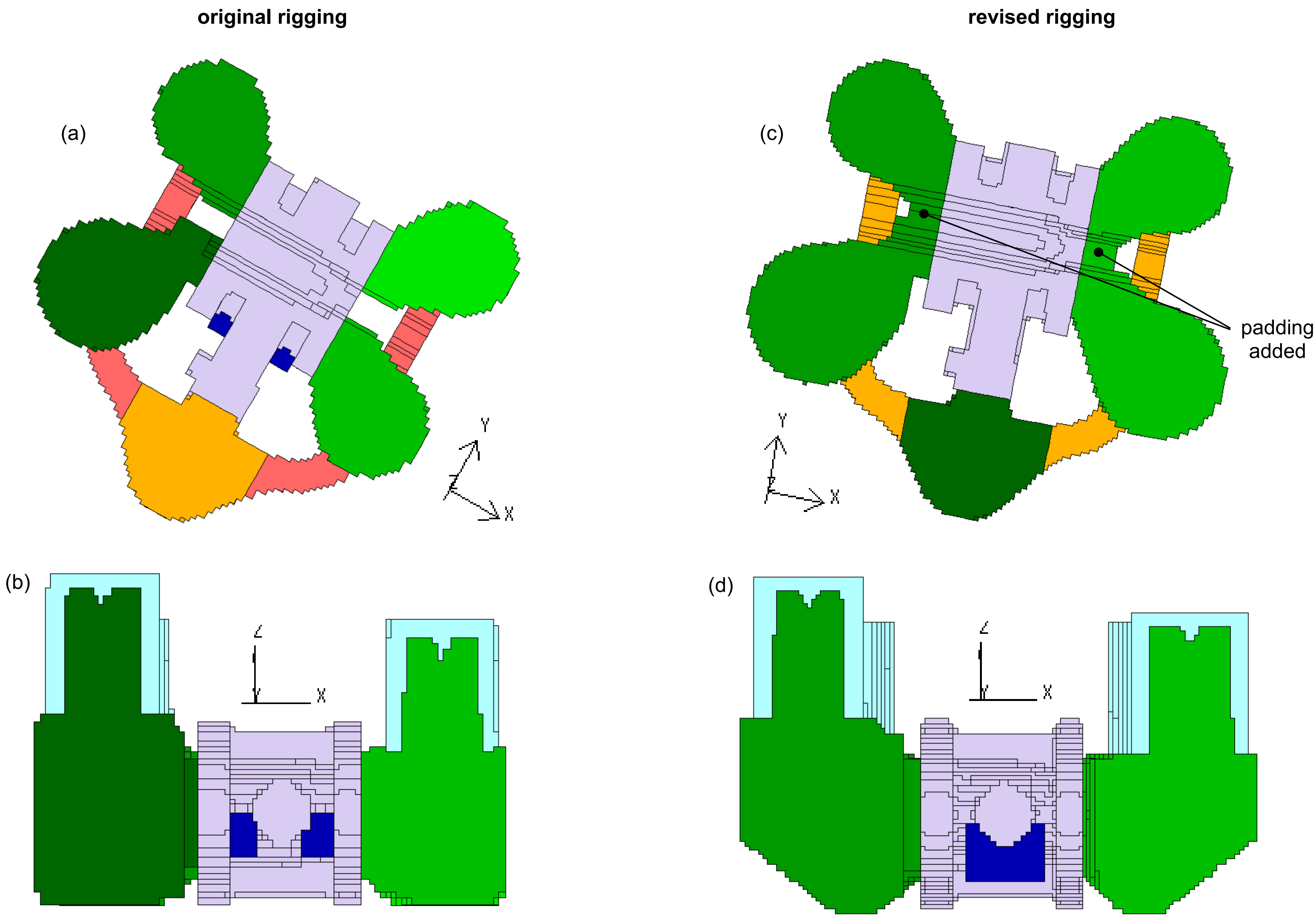

Figure 17 Comparison between the original and revised riggings: top views shown in (a) and (c), side views in (b) and (d).

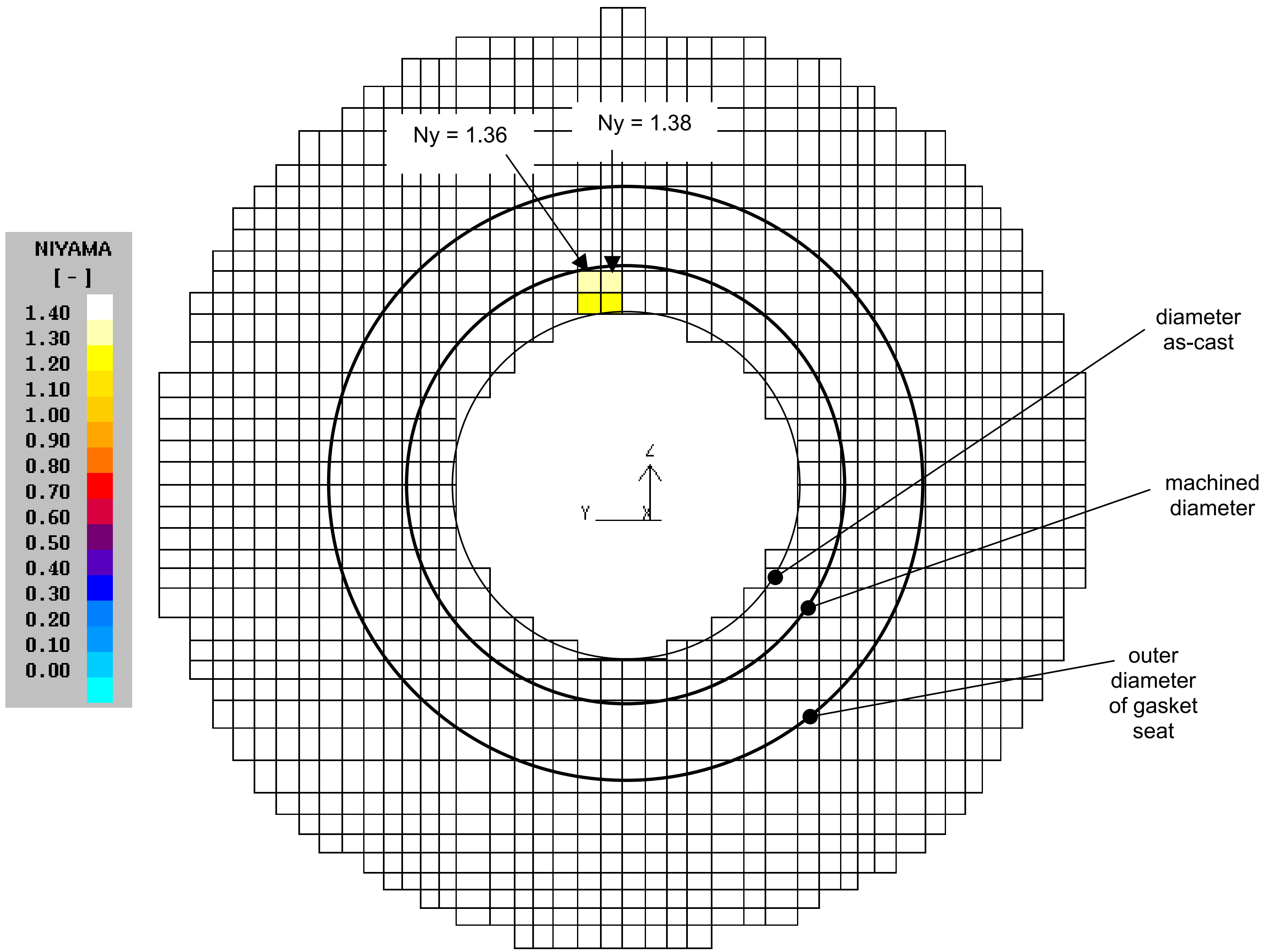

Figure 18 Revised rigging Niyama values on the machined flange face.

rigging was revised, and since then none of the castings has leaked. The casting process for both the original and revised riggings was simulated, and the minimum Niyama values in the problem area were around 1.2 – 1.4 for the original rigging, and 1.3 – 1.7 for the revised rigging. The results also showed that the Niyama values in the revised rigging were generally larger in the region of the leak than they were in the original rigging. Higher minimum Niyama values and fewer low-Niyama values both indicate that the soundness should improve, which agrees with the casting results. The Niyama values seem higher than one might expect, but it was determined that this could be remedied by modifying the mold properties and thermal boundary conditions in the simulation to more closely match the casting conditions. When this was done for the original rigging, the minimum Niyama values dropped to about 0.6 – 0.8. By further increasing the heat transfer coefficient, this value could be lowered further. Although the Niyama values produced by this study are a bit high, the trend of increasing Niyama values as casting soundness improves is still evident.

The second case study was an overpressure valve that leaked around the gasket that was intended to seal the overpressure nozzle in about 12% of the castings produced. Some of the castings that leaked had visible shrinkage on x-ray (ASTM level 1 or 2). Again, the rigging was revised and the problem was solved, and none of the 584 valves cast since the rigging was changed has leaked. When the casting process for the original and revised riggings was simulated, it was determined that the minimum Niyama value in the leaking area was about 0.1 for the original rigging, and about 0.5 for the revised rigging.

The third case study was a valve that leaked around the gasket seat on the flange face after the face was machined in about 22% of the valves cast. When these valves were radiographed, no visible shrinkage was evident. The rigging was revised, and again the leaking problem was solved. Simulations indicated that the minimum Niyama value for the original rigging was around 0.5 – 0.7 in the leaking area; the corresponding value for the revised rigging was about 1.4.

Based on the results of these case studies, there does appear to be merit behind the idea of a minimum Niyama threshold value for sufficient microporosity to cause leaks. The Niyama values from the first case study were high, but still indicated that the Niyama values increase when the casting soundness increases. The minimum Niyama values for the second case study drop down to the threshold value for macroporosity (0.1) for the original rigging. Due to the occurrence of visible shrinkage on some x-rays for this case, the cause of these leaks seems to be on the border between macroporosity and microporosity. The third case study, however, is an excellent example of leaks caused by microporosity, and the minimum Niyama threshold for this case appears to be on the order of one. Based on these case studies, a microporosity threshold minimum Niyama value on the order of 0.5 – 1.0 seems reasonable for low alloy steel castings. More accurate determination of this threshold value could be achieved by performing and analyzing a set of casting trials, similar to the procedure utilized in [2] to determine the threshold value for macroporosity.

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APPENDIX: Sensitivity of Niyama Criterion Values to Calculation Parameters

A study was performed to evaluate the sensitivity of the Niyama criterion to the parameters with which it is calculated. The study was performed by simulating the solidification process for a steel plate that was cast as part of the first SFSA/University of Iowa steel plate casting trials [2]. Simulations were performed using two different casting simulation packages, MAGMAsoft and AFSolid. For each software package, simulations were run both with and without simulating the filling process, and the Niyama criterion for each of these cases was evaluated at two different temperatures near the end of solidification. In addition, the dependence of the Niyama criterion on grid size was investigated using MAGMAsoft.

Before examining the results of this study, it is important to note some subtle differences between AFSolid and MAGMAsoft, including the default parameters these two software packages use to calculate the Niyama criterion. To begin, the thermophysical material properties provided in MAGMAsoft’s database are given as functions of temperature, while AFSolid provides constant thermophysical properties. Also, the default Niyama criterion evaluation temperature T_c in MAGMAsoft is 10% of the solidification range above the solidus temperature T_s. This can be expressed as

$$T_c = T_s + 0.1(T_l - T_s) \quad (1)$$

where T_l is the liquidus temperature. AFSolid, on the other hand, evaluates the Niyama criterion at the solidus temperature, or

$$T_c = T_s \quad (2)$$

Although the default values of T_c are different for AFSolid and MAGMAsoft, each package allows the user to specify T_c, so the values given by both Equations (1) and (2) were used for both packages. Finally, MAGMAsoft reports Niyama criterion values in the units $(K\ s)^{1/2}/mm$, while AFSolid uses the units $(K\ min)^{1/2}/cm$. The conversion between these two sets of units is given by

$$1\ (K\ s)^{1/2}/mm = 1.29\ (K\ min)^{1/2}/cm \quad (3)$$

For the purposes of comparison, all of the Niyama values reported in this appendix will be given in $(K\ s)^{1/2}/mm$.

The casting that was simulated for this study is the rectangular steel plate shown in Figure A1. This plate has dimensions 3” x 6” x 22.5”, and is fed by a riser 6” in diameter and 8.3” in height. The plate was cast from 1025 steel in a PUNB mold. The pouring temperature was 2840°F (1560°C), and the pouring time was 10 seconds. Radiographs taken of this plate were assigned an ASTM shrinkage rating of CB1, indicating that a small amount of visible shrinkage porosity is present along the centerline of the plate.

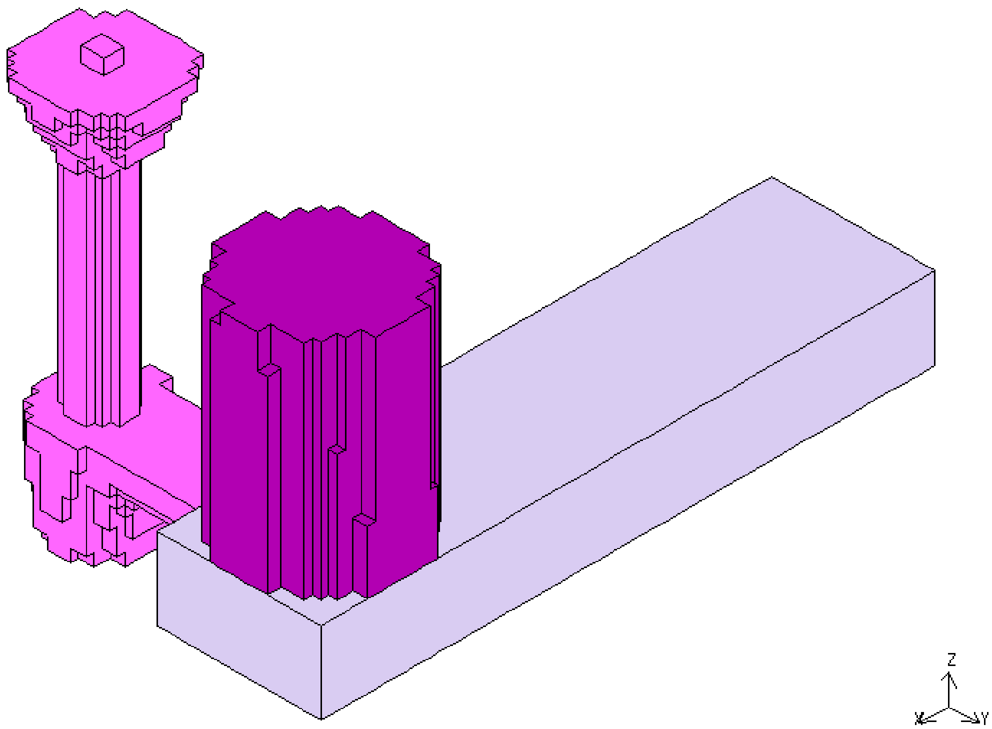

Figure A1   Simulated plate used for Niyama sensitivity analysis, shown with riser and gating.

In order to check the grid dependence of the Niyama criterion, the plate was simulated with MAGMAsoft using 100,000 cells and 1,000,000 cells (total number of cells, not number of metal cells). The calculations were both performed with filling, at the default MAGMA criterion evaluation temperature given by Equation (1). The Niyama plots for these two grids looked very similar, and the minimum Niyama values were very close (0.057 for 100,000 cells and 0.055 for 1,000,000 cells), indicating that the Niyama value was not dependent on the grid. The remainder of the MAGMA calculations and the AFSolid calculations were performed with 1,000,000 cells.

Plots of the Niyama criterion, computed with each software package using $T_c = T_s$, are shown in Figure A2. This figure depicts the side-view cross-section that runs vertically through the center of the riser and the plate. Note that even though both color scales run from 0 to 1.4, they are actually different because of the discrepancy in units of the Niyama criterion for each simulation package. Thus, 1.4 on the AFSolid scale is actually 1.09 (= 1.4/1.29, using Equation (3)) on the MAGMA scale. Taking this into account, the Niyama plots look qualitatively very similar. The minimum Niyama values for each simulation are also given in Figure A2. Because both simulations were performed using the same evaluation temperature T_c, the difference between the values (0.052 for AFSolid and 0.073 for MAGMA) is due solely to the difference in properties. AFSolid, which uses constant properties, returns a slightly smaller value than MAGMA, which considers temperature dependent properties.

The minimum Niyama criterion values for the different cases investigated in this study are summarized in Table A1. First, consider the effect of simulating with or without filling. Simulations are frequently run without filling to get a rough idea of how a casting will solidify, because the solidification portion of these simulations runs much faster than the filling portion. Notice that for AFSolid, there is almost no difference in the minimum Niyama values computed with and without filling. In contrast, MAGMA gives lower minimum Niyama values when filling is not used than when it is used, regardless of the temperature at which the Niyama criterion is evaluated. This indicates that MAGMA simulations run without filling will give a conservative estimate of the solidification process (i.e., the Niyama values will be a little lower, and thus the casting will appear to be a little less sound, when filling is not used). It is worth noting that this trend of increasing minimum Niyama values when filling is considered, versus when no filling is used, has

Table A1 Minimum Niyama values, in $(K\ s)^{1/2}/mm$, from two simulation packages using varied calculation parameters.

	With Filling		No Filling	
	$T_c = T_s + 0.1(T_l - T_s)$ *	$T_c = T_s$	$T_c = T_s + 0.1(T_l - T_s)$	$T_c = T_s$
AFSolid	0.042	0.052	0.040	0.050
MAGMAsoft	0.055	0.073	0.036	0.054

* T_c is the temperature at which the Niyama criterion is evaluated; T_l and T_s are the liquidus and solidus temperatures, respectively.

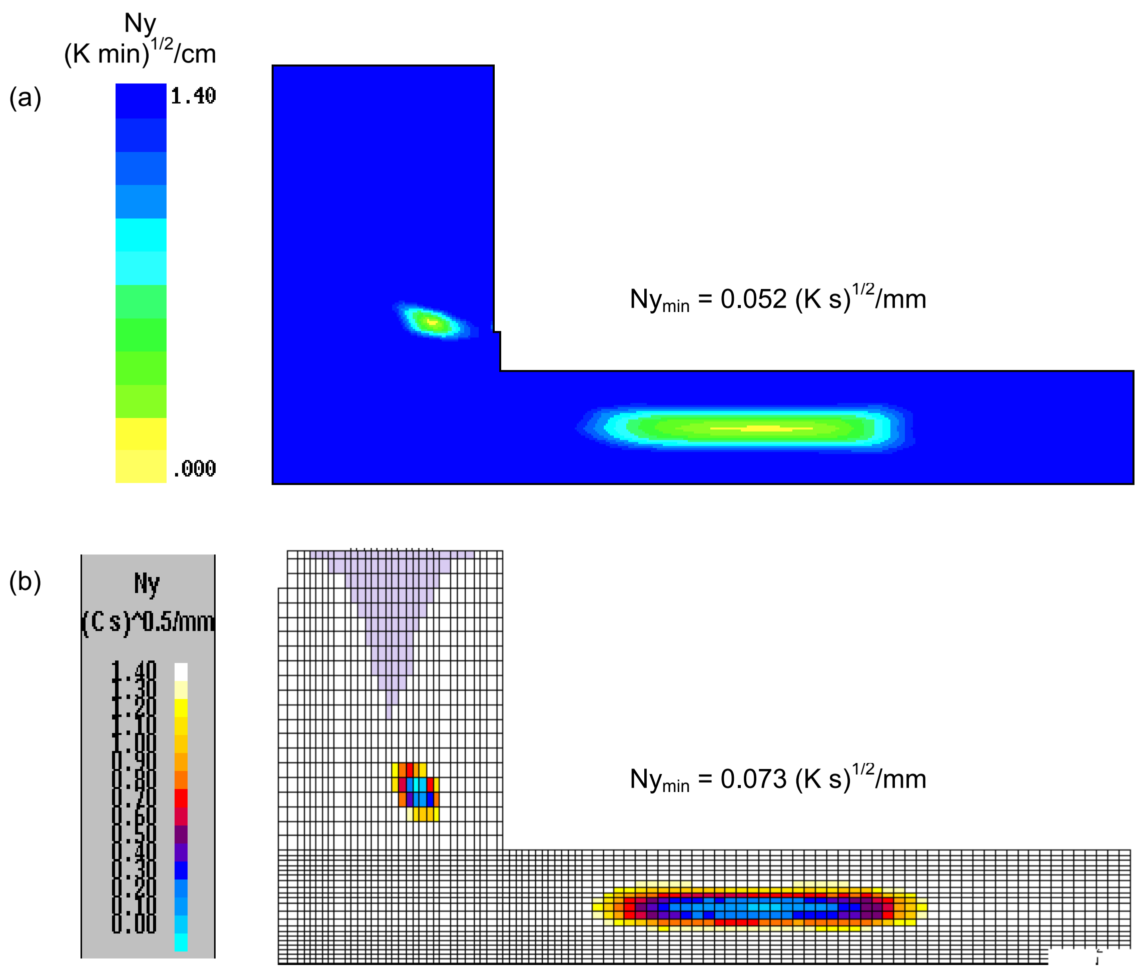

Figure A2 Niyama criterion plots for Ny evaluated at $T_c = T_s$, using (a) AFSolid, and (b) MAGMAsoft.

been seen repeatedly by the current researchers when running MAGMA simulations, for all ranges of minimum Niyama values.

Another trend evident in Table A1 is the difference that the Niyama criterion evaluation temperature T_c makes in the resulting minimum Niyama values. In every case, the minimum Niyama values are lower when calculated at 10% above the solidus temperature (according to Equation (1)) than when calculated at the solidus temperature (from Equation (2)). Thus, if all other parameters remain the same, a casting will appear to be slightly less sound in terms of the Niyama criterion if Ny is calculated at 10% above the solidus temperature than if it is calculated at the solidus temperature.

Finally, Table A1 shows that, for each particular set of parameters used to evaluate the Niyama criterion, the minimum Niyama values computed by AFSolid and MAGMAsoft are similar. When filling is not calculated, there is very little difference between the values computed by each simulation package. When filling is calculated, the AFSolid values are a little lower than the MAGMA values, indicating that the AFSolid results are slightly more conservative than the MAGMA results. The largest discrepancy occurs with filling, when $T_c = T_s$ is used to evaluate Niyama values.

With respect to the magnitude of the Niyama values listed in Table A1, it is worth noting that the results of this comparison would have been clearer if it had been performed with a shorter plate that had higher Niyama values. The differences between the values in Table A1 are nearing the accuracy limit of the Niyama criterion calculation, because the Niyama criterion asymptotes to zero. So it is difficult to discern if the difference between, for example, Ny = 0.052 and Ny = 0.073 is small or large. The simulations that provided these results were actually performed for other work, and this comparison was simply performed because the data were available.

In order to gain some insight into how these differences scale for larger Niyama values, MAGMA simulations were run for the same rigging with a shorter plate (3" x 6" x 16.5"). These simulations were run without filling at the two different criterion evaluation temperatures. The case run with T_c evaluated from Equation (1) resulted in Ny_{min} = 0.64, while the case with T_c evaluated from Equation (2) yielded Ny_{min} = 0.76. This is the same trend (i.e., higher minimum Niyama values when $T_c = T_s$ is used) seen in Table A1 for both AFSolid and MAGMAsoft. The magnitude of the difference is 0.12. While this is an appreciable difference, these values are still comparable.

Based on the information presented above, it can be stated that the trends seen in Table A1 are considered to be valid, and the values, while differing to some degree, are similar. This indicates that any simulation package can be utilized to calculate Niyama values, with a variety of calculation parameters, and similar results will be obtained. However, care should be taken when comparing Niyama values to make sure that they were calculated using similar parameters.