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Reducing Leaks in Cast Pump and Valve Bodies using Solidification Simulation

Raymond Monroe, Steel Founders' Society of America
780 McArdle Unit G
Crystal Lake, IL 60014
monroe@sfsa.org
Malcolm Blair, Steel Founders' Society of America
Christoph Beckermann, The University of Iowa

ABSTRACT

Most steels and corrosion resistant alloys are cast prior to being shaped into their final geometry by forging, machining or fabrication. Since these typical manufacturing processes are not able to form complex internal passages needed for pumps and valves, casting are used. Casting pump and valve bodies allows the use of cores of bonded sand to form the complex internal features.

Casting complex geometries requires careful design to manage solidification and achieve the product performance required. Quality of castings is normally assessed using techniques like radiography to assure component integrity. Castings used for the production of valves can leak even when they pass a full gamut of stringent quality requirements. Unanticipated leakage from valves and pumps is costly and disruptive.

Solidification simulation calculating the Niyama criterion, based upon the thermal gradient and the cooling rate of in a casting during solidification, can predict shrinkage. This provides a way to assess casting quality prior to production at sensitivity levels unavailable from radiography or ultrasonic methods used after production. Leaks due to microshrinkage porosity can be managed during the casting production planning through the use of solidification modeling.

INTRODUCTION

Valves and pumps that leak in service are a perennial problem in industry. This is especially troublesome when the valve or pump is in the early stages of its expected life and is used in processing dangerous or hazardous materials. Leaks from the pump or valve body may be from the casting used to construct the component. Castings are widely used for producing pumps and valves.

Most steels and other special alloys used for the production of pumps and valves are cast. Often these materials are cast as ingots or as long products like bars and then forged, machined and assembled for service. Traditional forming methods such as machining and forging are limited in their ability to form complex internal passages. There are no good ways to reach inside a component to create the complex geometries required for performance. Castings are commonly used because it is possible to make a core from bonded sand that replicates the geometry of the desired internal flow passage. This allows the production of efficient fluid handling systems with complex internal passages.

Forming components from ingots with forging or machining provides some material advantages over castings. The material costs of melting and casting an ingot is lower than using complex tooling to cast the component to the geometry desired. More fundamental is the need to manage the solidification to achieve the desired material properties. Casting ingots allows the ingot design to optimize the material condition and achieve the most sound and uniform properties. Casting the near final shape is more difficult since it means that we must manage the solidification of a complex geometry designed for the final function. In particular, as castings solidify the solid is less dense than the liquid and so the shrinkage associated with this transition must be managed through clever casting design.

Valves are particularly problematic in casting production and pumps are also challenging. The easiest geometry to cast sound is a wedge shaped design where the solidification proceeds from the thinnest section to the thickest section. By putting a large riser on the thick section, the shrinkage can be isolated to the riser and removed from the casting. Complex castings require solidification management to avoid shrinkage in the casting. Valve castings are problematic because their design includes isolated thick sections in the seat area and flanges that are prone to shrinkage.

Historically, pump and valve manufacturers through their purchasing expertise limited their suppliers to sophisticated casting producers with demonstrated capability and quality. Global sourcing and changes in corporate practices have led purchasers to an increasing reliance on purchasing standards and less reliance on qualified vendor selection. Radiographic testing (RT) while not uniformly required by specification is a common practice for suppliers in North America for these castings. Radiographic requirements for fluid handling component castings have been seen as the most useful tool to reduce the risk of leaks. Ultrasonic testing (UT) has also been used. These Non-destructive examination (NDE) requirements have been shown to not be capable of detecting conditions that result in leaking castings.

Pump and valve bodies are designed on computer aided design tools (CAD) and result in solid models of the desired components. These solid models can be used by the foundry to design the solidification management system traditionally called the rigging or risering system. Solid models of the casting design can be "solidified" using solidification simulation to understand the issues involved in the casting production. The casting design can be evaluated with the rigging to assess the soundness of the casting as designed. This has been shown to be able to avoid leaks by ensuring adequate casting soundness in the critical areas of the casting.

Radiography

The most common inspection method to ensure that castings are sound is RT. Taking an x-ray of the part to look inside and see if there is porosity or other problems is the traditional tool for quality assessment. Early work by Beckermann to correlate RT of plate castings with solidification simulation showed problems that were unanticipated.[1] Several different foundries made plates of various lengths and thicknesses and these were evaluated using solidification simulation. The results of the RT evaluation of the 128 cast plates were inconsistent. This led to the evaluation of all the RT films using the technique of gage R&R, determining the repeatability and reproducibility of the RT standards.

This was a conservative estimate of the problems with RT since the test was done on existing films and the films were made on plates and not on more complex geometries like a pump body. There was unanimous agreement on only 16 of the 128 plates examined, 14 that had no indications and 2 that were rated at the grossest level of shrinkage, level 5. The statistical analysis of the exercise for RT with 5 levels showed a one-sided student-t 95% confidence interval for all 128 films was 1.42 levels. For the critical discriminating levels of 1 through 4, the resulting confidence interval was in excess of 1.5 RT levels as seen in Figure 1.

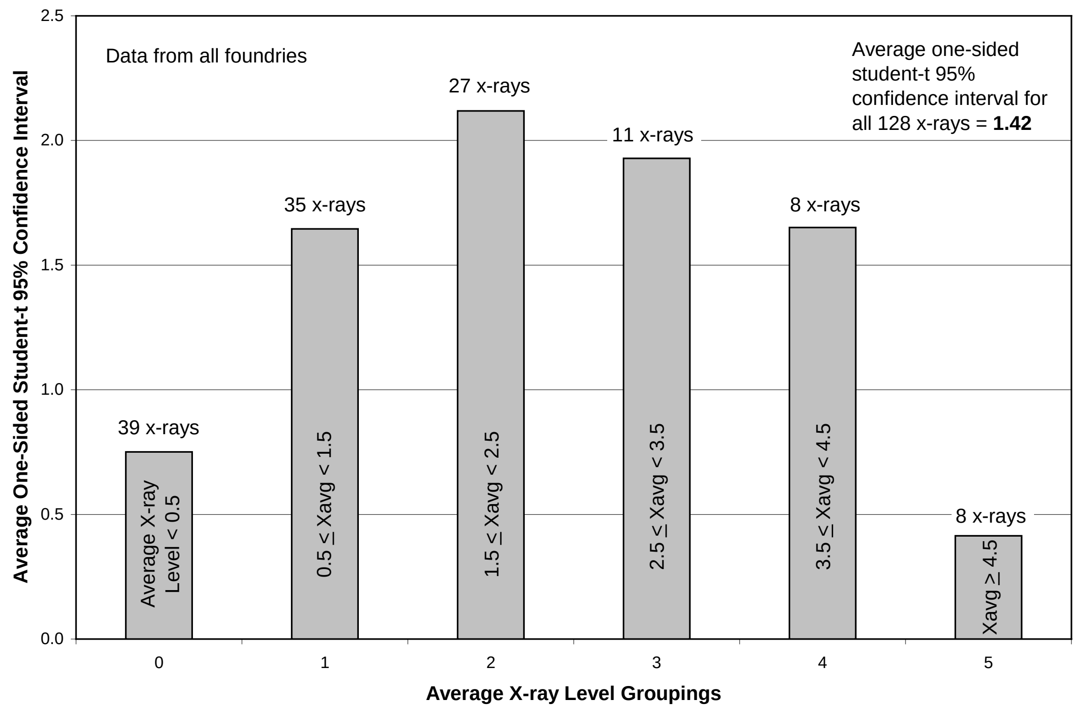

Figure 1: Confidence intervals of radiographic level ratings grouped by the average level reported

This is not the only problem with RT evaluations for soundness of fluid handling components made from castings. The RT standard levels are not based on any engineering concept or measurement. The RT levels of the specifications are workmanship standards and are unrelated to performance. Even if the current RT standards could be applied reproducibly and give an unambiguous rating, the rating was not developed to predict the performance of structural components. More pertinent, the RT standards were not developed to predict or to be used to control leaking in cast valve or pump bodies.

Finally and perhaps most troubling is that the RT techniques to make sure the film has adequate resolution requires that the RT procedure include a penetrameter to demonstrate a film and exposure sensitivity of 2%. This means RT will not reliably detect porosity or other casting characteristics that may be problematic if they are smaller than 2% of the volume in the cross-section. Castings can be radiographed and the films show no indications but still have micro-shrinkage that leads to leaking in service.

Leaking Castings

As a part of the effort to improve casting performance and design, solidification modeling had been studied by Beckermann and this was the basis of the statistical evaluation of RT discussed above.[1] In order to extend the use of radiography and attempt to control casting design and processing to avoid leaks, additional work was undertaken to examine valve castings that were radiographically sound but exhibited leaks after production.[2]

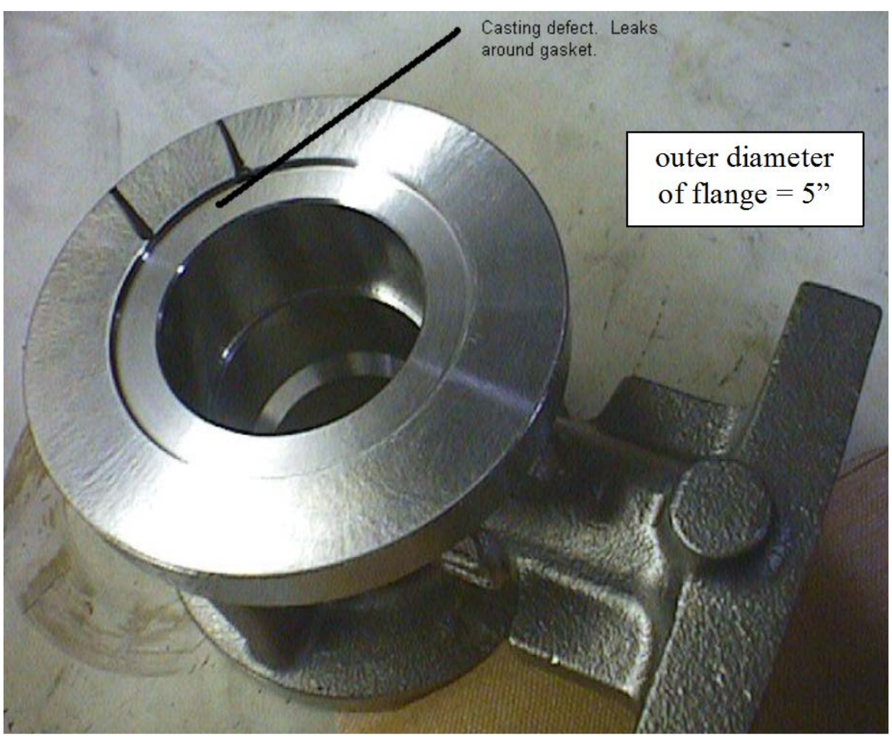

Figure 2: Example of a radiographically sound cast valve body with leaks

Examples of the problem of leaking cast valve bodies that are not detected by RT inspection were examined to see if the occurrence could be predicted by solidification simulation. In one case, valve bodies cast in J93000 (CG8M) were prone to leak after machining. The leaks in 9 of 22 valve bodies (22%) were around the gasket on the flange face as seen in Figure 2.

A casting was sectioned and examined to determine the cause of leaking. Microporosity was observed and was responsible for the leaking. This porosity was not large enough to be apparent in RT but was severe enough to leak. The microporosity is shown in Figure 3.

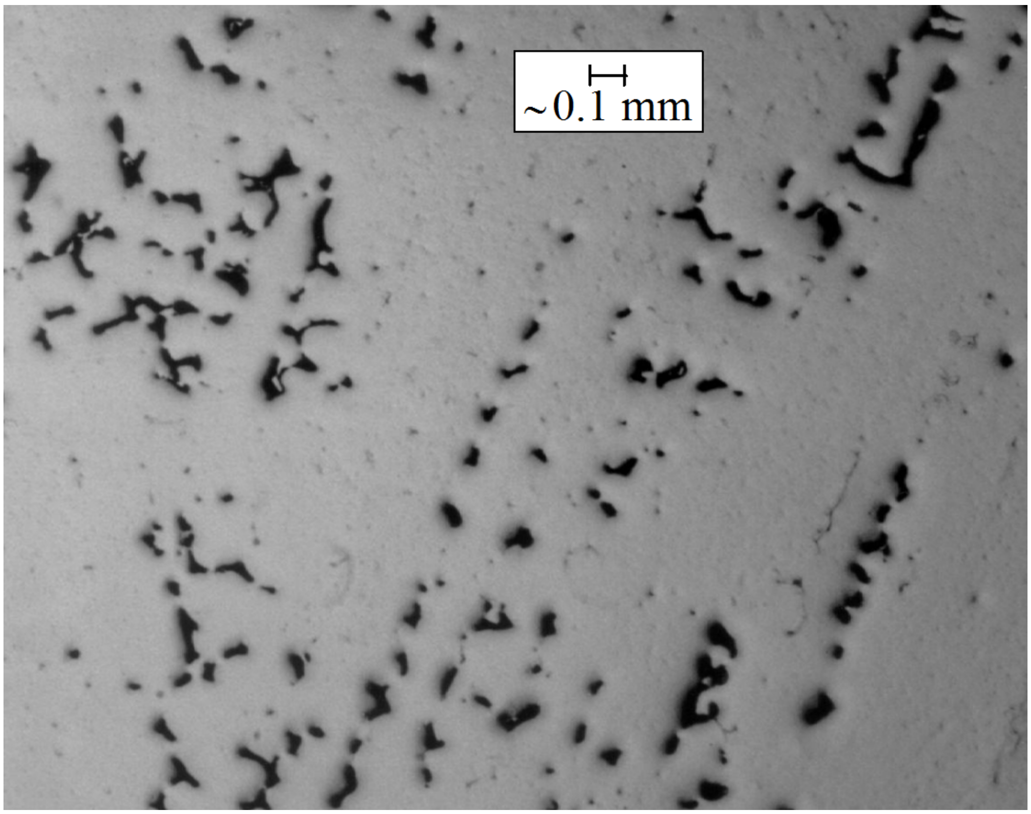

Figure 3: Photomicrograph of microporosity in the leaking valve casting

Steel casting producers extensively use solidification modeling to design the casting process ,including attached risers, to feed the casting and avoid shrinkage. The techniques for analyzing casting process design were expected to be capable of identifying areas prone to microshrinkage.

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 shown in Equation 1,

$$Ny = G/\sqrt{\dot{T}} \qquad (1)$$

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 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). Because the Niyama criterion can predict both micro- and macroporosity, some larger value of Ny_{min} serves as a threshold for the occurrence of microporosity sufficient to cause leaks.

The foundry process for the leaking valve casting was simulated using MAGMAsoft. The Niyama values on the flange face that leaked after machining are shown in Figure 4. 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 2 (i.e., above the machined hole).

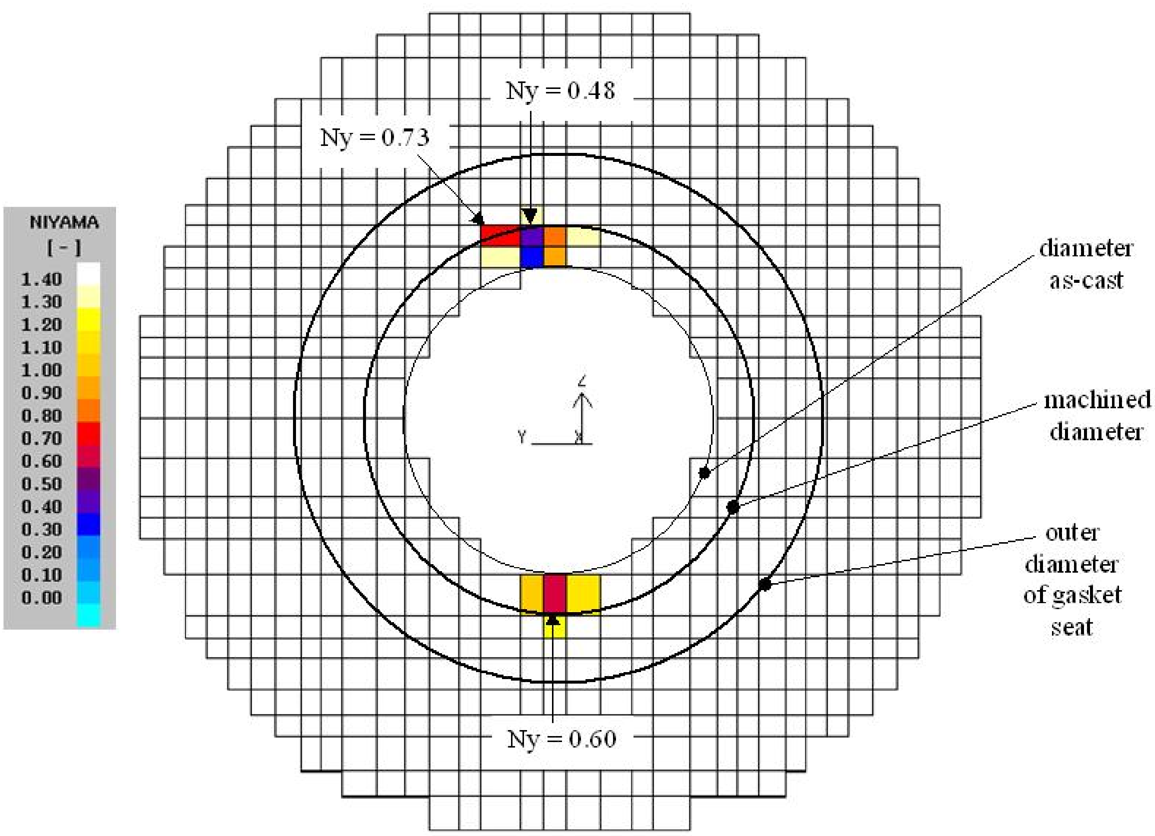

Figure 4: The solidification results of the original process design for rigging that resulted in leaks in the valve body

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. The chill arrangement was also changed, from two separate chills below the valve to a single chill, which was moved further underneath the valve. Another change is the reshaping of the lower outside portion of the risers.

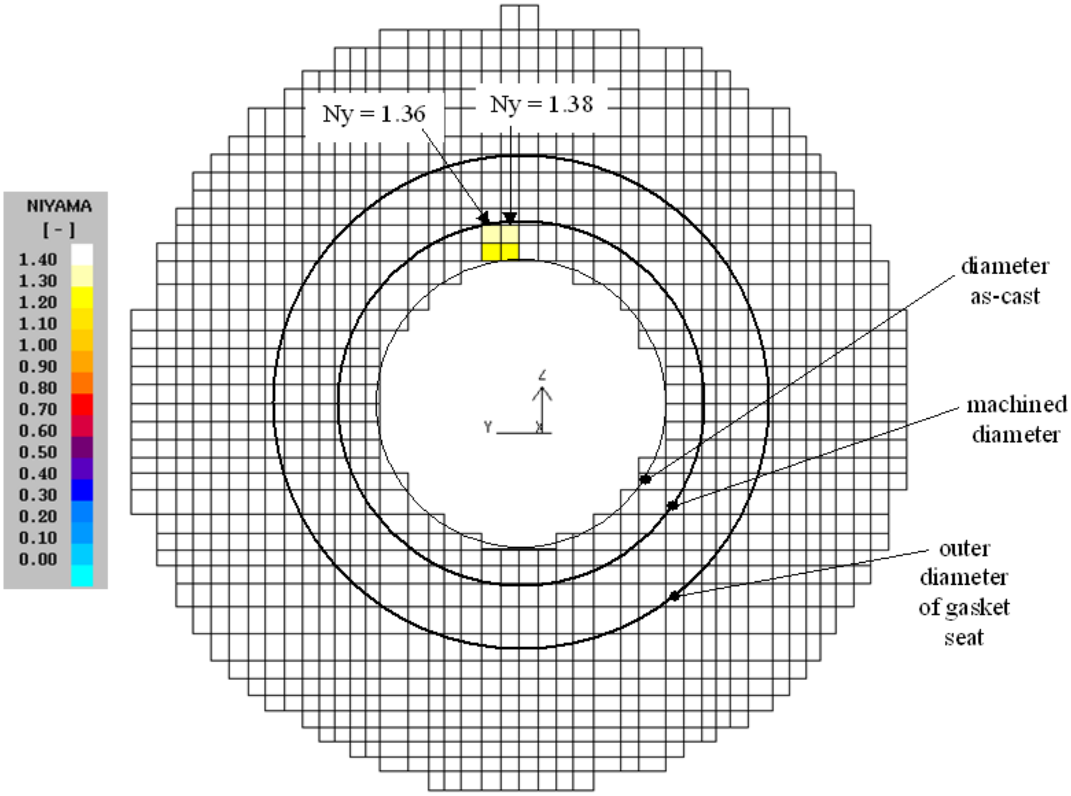

Figure 5: The solidification results of the revised process design for rigging that resulted in no leaks in the valve body

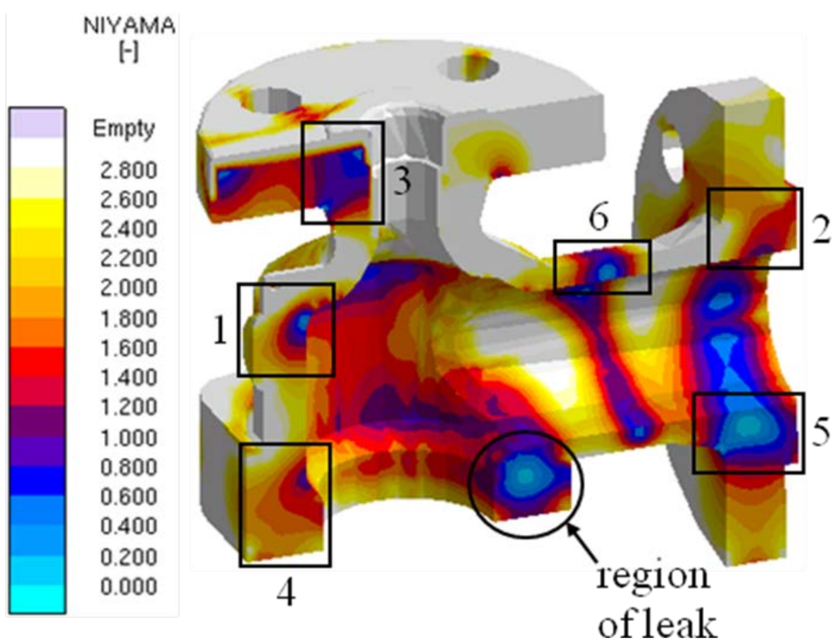

Figure 6: Niyama evaluation of a leaking valve identifying other areas of microshrinkage

This new rigging was simulated in MAGMA, and the resulting Niyama values are shown in Figure 5. 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.

Another example is a cast valve body made from N24135 (M35-1) where one valve of 8 leaked. This leak was examined and again determined to be the result of microporosity. The casting was analyzed with MAGMA and areas of low Niyama values identified. The leaks occurred in a low Niyama region with values well below 1. Other areas of low Niyama were also identified as seen in Figure 6. These were subject to microstructural examination and they were all found to contain microshrinkage. One typical region of low Niyama labeled 6 in Figure 6 is shown in Figure 7.

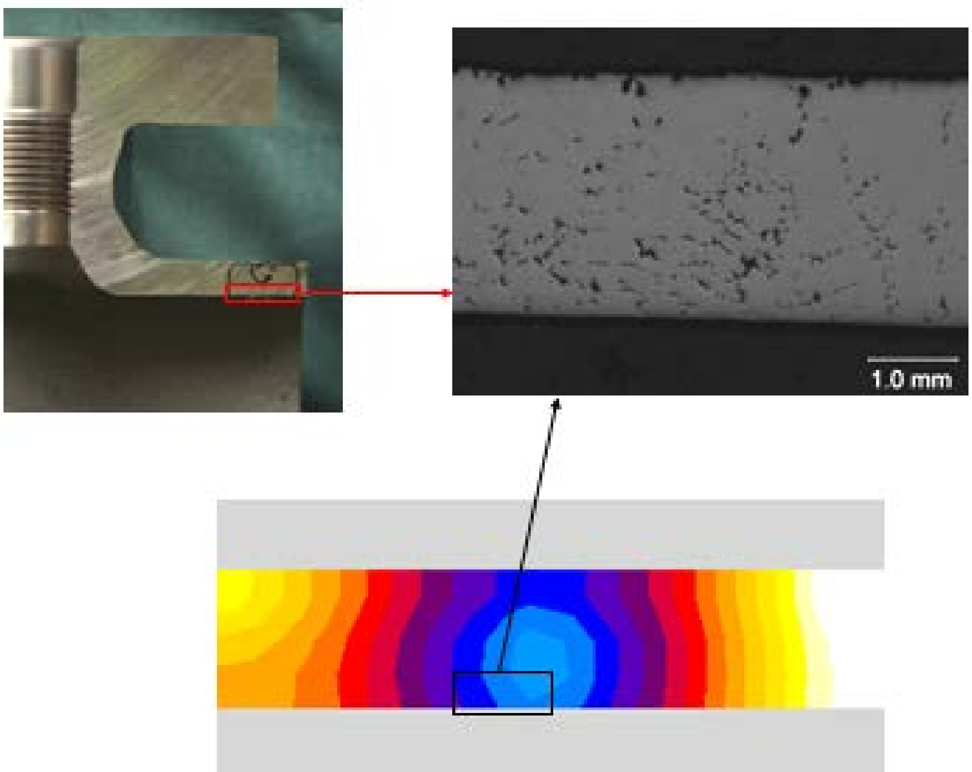

Figure 7: Microshrinkage Porosity in a Non-leaking section of the casting identified as Region 6 in Figure 6

Niyama criteria can be used to determine if there are regions of a casting that would be prone to form microshrinkage and be liable to leak. Niyama criteria is however not capable of predicting gas porosity, hot tears, inclusions or other casting conditions that might result in leaks. Calculating Niyama criterion accurately requires alloy thermal data. This data is expensive to acquire and not generally available for the casting alloys used in severe corrosion resistant service. Many alloys have been characterized so this type analysis can be accurately completed on valve and pump body castings. Included in the alloys that have been characterized are: J03003 (WCB), J42045 (C5), J82090 (C12), J91171 (CA15), J92205 (CD3MN), J92900 (CF8M), J94651 (CN3MN), N08007 (CN7M), N26625 (CW6MC), N30002 (CW12MW), N24130 (M30C), N24135 (M35-1), and J30003 (N3M). In addition, it is critical to have a capable team that can correctly use the solidification modeling tools and get a usable result. Issues like the correct units, the choice of mesh size and time steps, the mold properties, the process conditions in production, etc., all must be correctly input to get accurate results.

It is often not possible to get high Niyama values in every place in the casting. The design of the geometry and the manufacturing constraints may not allow all parts of the casting to meet a value set too high. It is key to identify the critical parts of the design that require the highest values. It may be necessary to modify the design or the process to get a casting produced that is capable and affordable. Collaboration between the valve user, the valve maker and the casting producer is required to get the best outcome.

Conclusions

The knowledgeable use of solidification modeling and the application of the Niyama criteria can be used in lieu of RT testing to assure cast valve and pump bodies are free of solidification microshrinkage that can result in leaking. Niyama values greater than 0.1 for most alloys will ensure that the casting is sound when subject to RT. Niyama values may need to be greater than 1 for most alloys to ensure the casting does not leak as a result of microshrinkage related porosity.

Bibliography

[1] R. A. Hardin, S. Ou, K. Carlson, and C. Beckermann, “Relationship between Casting Simulation and Radiographic Testing: Results from the SFSA Plate Casting Trials”, *1999 SFSA Technical and Operating Conference*, 1999.

(2) K. Carlson, S. Ou, R.A. Hardin, and C. Beckermann, “Development of a Methodology to Predict and Prevent Leaks caused by Microporosity in Steel Castings”, *2001 SFSA Technical and Operating Conference,* 2001.