Proceedings of the 2012 Joint Rail Conference
JRC2012
April 17-19, 2012, Philadelphia, Pennsylvania, USA

JRC2012-74122

IMPROVING CASTING INTEGRITY THROUGH THE USE OF SIMULATION SOFTWARE AND ADVANCED INSPECTION METHODS

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Abstract

Casting integrity is essential for providing components that meet design criteria for strength and fatigue performance. As the leading method of manufacturing metal components in the rail industry, maintaining quality and consistency is a continuing struggle for car owners and builders. Internal shrinkage and voids due to insufficient metal flow are issues commonly found in casting molds which are not designed or utilized properly. Using casting simulation software, potential issues can be discovered upfront and robust mold designs can be created that offer a tolerance for the variance or variations in casting conditions that are present in the real world.

Strato, Inc. has extensively studied the effectiveness of these simulations in foundries through advanced inspection techniques. It is evident that casting simulations can not only locate, but also explain shrinkage cavities and voids through material density plots and inspection of directional solidification via critical fraction solid time plots. This approach is markedly more efficient than the traditional trial and error method, where mold makers rely on experience and destructive testing to develop acceptable mold designs.

With recent advances in simulation software, the labor and time-intensive ways of the past have been supplanted by a more scientific approach to the problem. Understanding the fluid dynamics and thermodynamics of the casting process provides a means of creating a stable, repeatable final product. This higher quality final product can be delivered faster to the customer and at a far less expense by identifying problem areas prior to the tooling and sampling processes. Case-studies explored by the Strato engineering team suggest that using this software decreases the fallout rate.

Background

Historians believe that as far back as 4,000 B.C., ancient Egyptian and Chinese cultures used a form of investment casting to create intricate objects that would have been otherwise impossible to make using sand molds. Over the centuries, the introductions of new methods and technologies have continuously improved the quality of castings. Risering and gating theory, insulation, cold blocks and controlled pouring parameters are examples of some advances. In recent years, computer processing power and finite element algorithms have opened the door to intriguing opportunities in our approach to the design and analysis of molds. Using casting simulation software, mold designers, foundrymen, and engineers are able to examine the fluid dynamics and thermodynamics of a pour without picking up a ladle.

Introduction

Castings offer a unique balance of quality and cost, which is attractive to many rail car builders and owners alike. If the process is utilized correctly, complex fabrications can be poured as castings, allowing for both time and cost savings. However, geometric complexity can lead to challenges in achieving repeatable quality in castings. Metal shrinkage caused by undesirable temperature gradients during the pour and solidification process can result in voids in the casting. These voids can affect the strength and fatigue life of a part, particularly if they are located in a high-stress zone.

Traditionally, foundrymen and mold designers examine a part visually and use their experience to develop gating and risering. The molds are then constructed and samples are poured. Sectioning is performed on the samples in order to inspect their integrity. This can lead to long sampling periods and numerous pattern modifications that may be necessary for more complex parts.

Scope

While this paper presents examples that give us confidence in the veracity of simulated results, the scope of this paper is not to confirm the validity of prior research on this subject. The number of samples analyzed would need to be much greater to make such a statement. This paper will address how the variance in initial casting conditions may affect the output of certain simulations. SolidCast, the software used to simulate the pour and solidification, was developed by Finite Solutions[3]. This paper will also highlight several best practices in casting simulations using SolidCast version 8.1. The molds examined produce castings ranging from five pounds to 150 pounds. All examples discussed are mild steel lost wax investment castings.

Inspection of castings may be done in several ways in order to confirm the results of the simulations. An example is presented where sectioning is used to show a large void. Non destructive testing including radiography, phased array ultrasonic testing, and SCRATA[5] comparator plates are also used to validate simulated results. These non-destructive tests were performed by certified NDT inspectors.

Procedure

The setup of a simulation is critical for achieving accurate results. Variables such as node size and material properties including the critical fraction solid point can impact the simulation. In SolidCast, node size is the relevance, or density, of the mesh. The mesh should be such that a minimum of three nodes span the thinnest cross section of the model. Having more than three nodes across the thinnest section will provide more accuracy. However, this comes at the expense of processing-time. The critical fraction solid point is the temperature at which metal ceases to flow. Note this temperature is higher than the solidification point. For carbon steels, a critical fraction solid point of 40% is suggested by Finite Solutions.

Case Study I: Using Critical Fraction Solid Time to Understand Shrinkage in Lower Level of a Casting Tree

A useful tool in SolidCast for examining simulation results is the Critical Fraction Solid Time plot. Note that the solidification temperature of this material is 2770 °F. The plot in Figure 1, which illustrates the casting tree, shows the material that is still above the critical fraction solid point of 2796 °F at a specified time in the solidification. Metal that is above 2796 °F is still capable of flowing. A lost wax casting tree is defined as a stack of identical parts connected via a central trunk, or gate, which increases pouring efficiency while containing pattern costs. A flow-path leading back to the gate shows that there is a means of feeding the area in question.

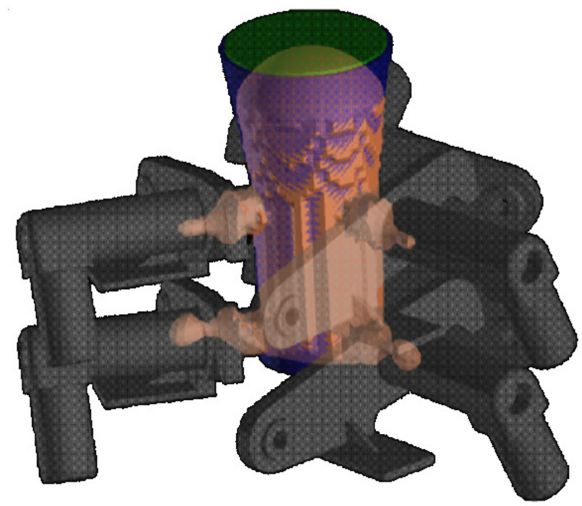

Figure 1: Critical Fraction Solid Time Plot of Casting Tree

As the tree cools, the plot shows a neck appearing in the lower castings. As the neck gets thinner, the part has less of a means of being fed by the gate. Eventually, this neck closes and what is left is a pocket of liquid metal. With no further flow from the gate, the pocket is forced to cool at a constant volume. The result of this cooling is the large void we see in the sectioned casting in Figure 2.

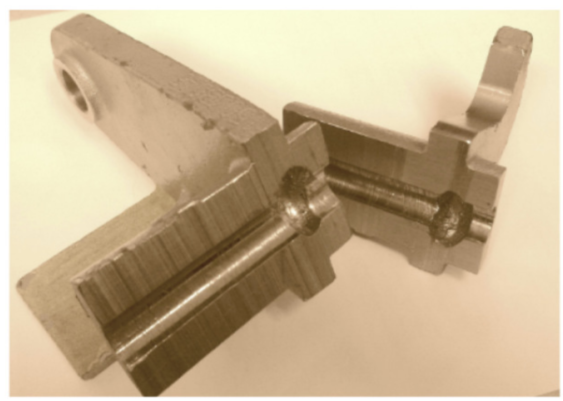

Figure 2: Sectioning Showing Void in Part from Figure 1

Improvements in the connection point between the casting and the tree resulted in a sound casting. The Critical Fraction Solid Time plot for the improved casting which corrected the formation of the neck can be seen in Figure 3 along with the new sectioned casting, Figure 4.

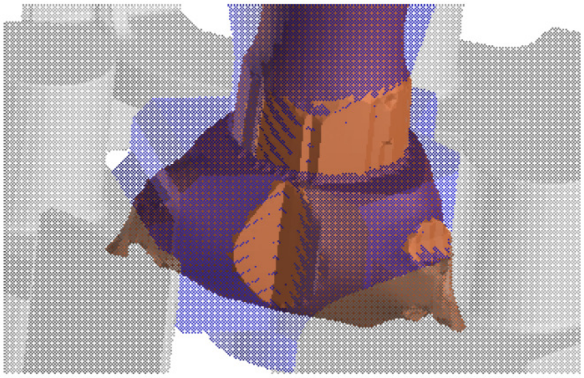

Figure 3: Close Up View of the Critical Fraction Solid Time Plot Showing the Improved Casting

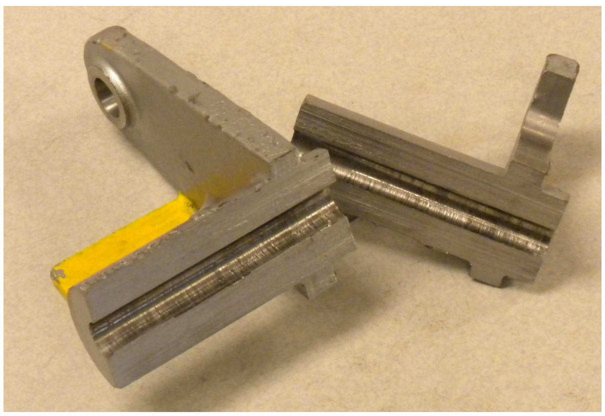

Figure 4: Sectioning Showing Improved Sound Casting

Case Study II: Using Feeding Zones to Predict Shrinkage – Insufficient Number of Risers

Another method for predicting shrinkage using simulation software is to plot feeding zones. A feeding zone is a portion of the casting that, due to the geometry, would need a riser. The foundry pouring this casting was experiencing high fallout rates due to shrinkage during the sampling and development phase. Using their risering and gating design as well as pour conditions, simulations are able to show the location of this shrinkage. This alone can take a lot of the guess work out of the design of gates and risers.

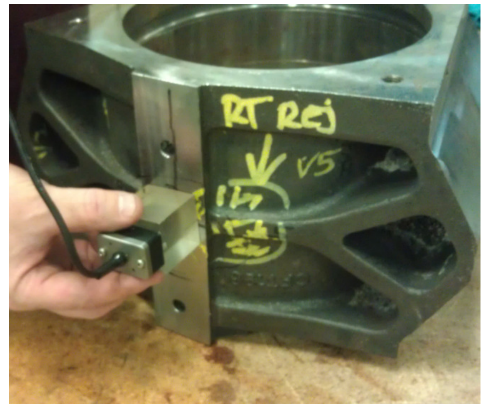

Figure 5: Phased Array Ultrasonic Testing Probe

The shrinkage that puzzled the foundry was occurring in the region being inspected in Figure 5. Using phased array ultrasonic testing, it is possible to identify shrinkage in a non-destructive way. This testing method works by sending ultrasonic waves that reflect and refract at the boundaries of the casting to reveal voids that would be otherwise invisible to the naked eye. Any changes in density can be identified by a mark on the output display screen. Figure 6 shows this output screen of the ultrasonic testing, showing a void in the material. Note that the two large, dark red areas on the plot are the inner and outer surfaces of the part. The arrow points to the shrinkage.

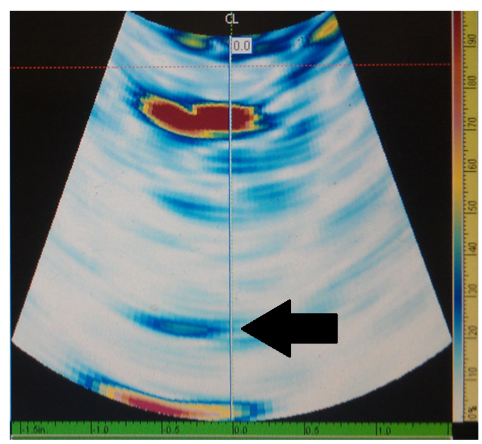

Figure 6: Output of Phased Array Ultrasonic Testing Showing Shrinkage

Another non destructive detection method that was used to inspect this casting was radiographic technology. Better known as X-Ray, radiant energy with a short wavelength is able to penetrate the casting and display abnormalities to aid in the process of flaw detection. The results from the ultrasonic inspection were verified once a level 5 defect was found by means of the X-Ray method.

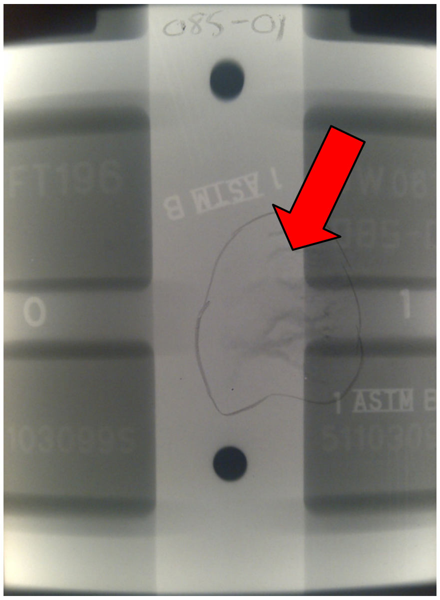

Figure 7: Radiographic Image Showing Level 5 Shrinkage.

Using simulation software to understand the dynamics behind the shrinkage, the location of the shrinkage is first confirmed. Figure 8 is a material density plot of the part in question. The volume shown in yellow is the material at which the density is less than 99.5% of what solid metal would be. This percentage, as defined by Solidcast, represents the point where detectable shrinkage will most likely occur. This decrease in density is indicative of shrinkage. The question posed by this plot is: Would increasing the riser size or moving the gates closer to the location of the shinkage solve the problem?

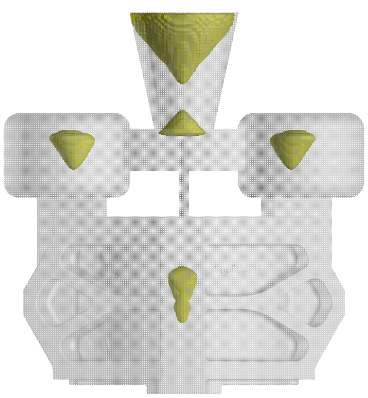

Figure 8: Material Density Plot Showing Shrinkage in Casting

The answer to this question can be found by analyzing the feeding zones of the part. Feeding zones are sections of the casting which require a riser in order to solidify without voids.

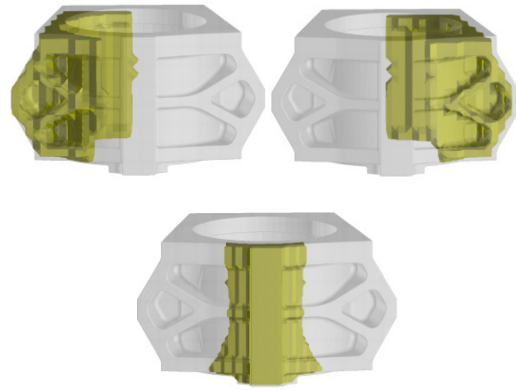

Figure 9: Simulation Showing Three Feeding Zones

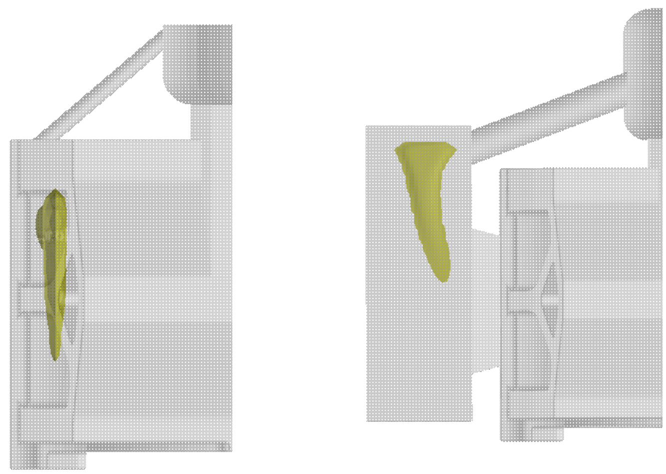

Figure 10: Shrinkage shown in the casting (Left) vs. the shrinkage removed by a successful riser (Right).

Using the process for calculating feeding zones in SolidCast, it is clear that there are three distinct zones for this part. Feeding zones are identified in SolidCast by pattern-recognition software that classifies isolated areas which require feeding based on cross sectional thicknesses. As risers were only attached to two of these three, it could have been expected that porosity would occur in this third zone. To confirm this, a third riser was added to the zone with shrinkage as shown in Figure 10. The simulation with this new riser shows that shrinkage has been successfully removed from the part. Implementation of this improved design is currently in process and a correlation between the simulation and the improved casting is unknown at this time.

Case Study III: Using Feeding Zones to Predict Shrinkage – Modifying Riser Geometry

In many cases, shrinkage is evident in castings that have risers in the correct locations. The primary cause of this may be due to insufficient riser geometry. If a riser does not have enough mass to feed the area in question, there will be shrinkage. A material density plot can be seen in Figure 11. This plot predicts shrinkage in two areas of the casting using ideal initial conditions. These conditions, which were used for this simulation, are as follows:

- Pour Temperature: 2876 ^{o}F
- Shell Temperature: 752 ^{o}F
- Pour Time: 9.4 seconds

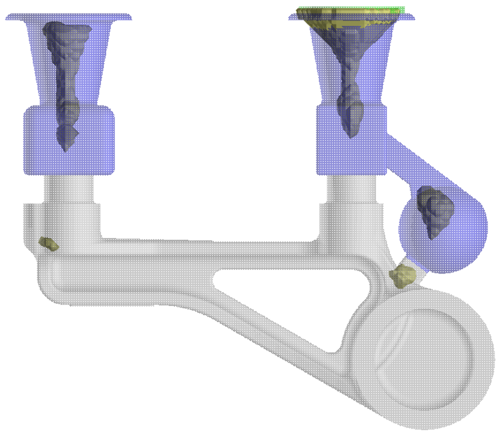

Figure 11: Material Density Plot Showing Shrinkage in Two Areas of the Casting at Nominal Conditions

The shrinkage on the left side of Figure 11 can be seen on the surface of the part in Figure 12. This defect was uncovered during the machining process and was not visible on the casting surface after pouring.

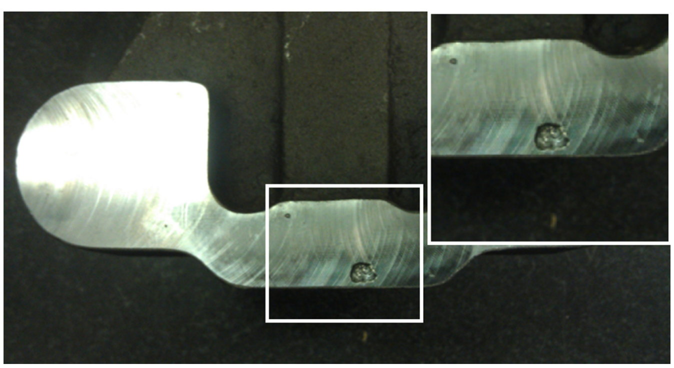

Figure 12: Sectioning of Casting Showing Shrinkage

The second area of porosity was able to be seen at the surface; SCRATA plates were used to define the defect level rating in this area for surface gas porosity. Figure 13 shows this surface porosity with a defect rating level of CII.

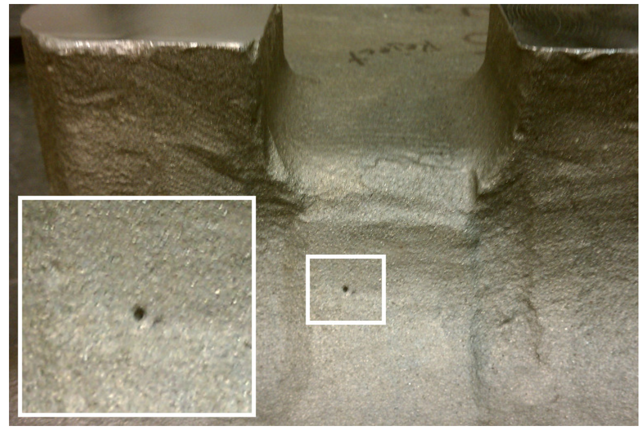

Figure 13: Surface Porosity

In order to understand the cause of the shrinkage, feeding zones were again used to verify the risering. The feeding zone calculation in Figure 14 suggests that the part is in fact risered correctly. A riser is attached to each of the five zones. With that knowledge, the size of the risers can then be adjusted so that the part solidifies correctly.

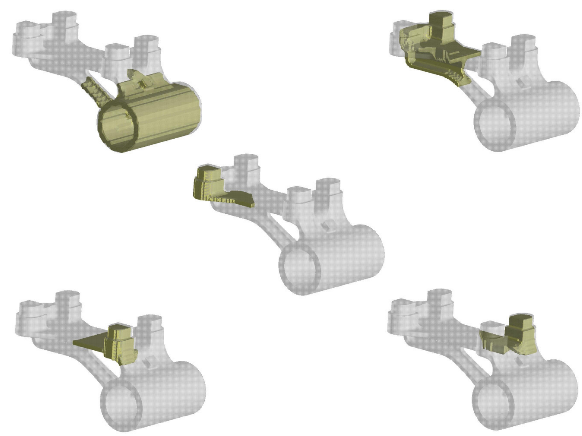

Figure 14: Five Feeding Zones Show that Riser Locations are Correct

By taking into account the information provided by inspection of the casting and software outputs, design of the gating to remove all shrinkage can be maximized. In this case, the connection points where the risers meet the casting were increased to allow for improved solidification. Also, the total volume of the risers was increased by 16% which allowed the ideal flow of heat to encourage the casting to solidify without the formation of shrinkage. The new gating design can be seen in Figure 15. Like Case Study II, this improved design is currently being implemented at the foundry. The improved castings integrity cannot be compared with the simulation at this time.

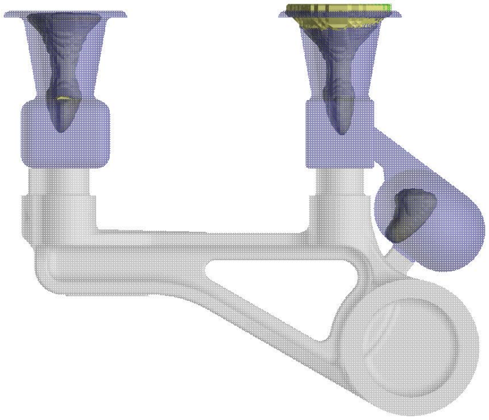

Figure 15: Modified Rigging Showing No Shrinkage In the Casting.

Case Study IV: Effects of Varying Initial Conditions

In examining the casting process, there are many variables that can be investigated while running casting simulations in order to bracket the initial conditions that are encountered in foundries. The three main conditions analyzed in this case study are Pour Temperature, Shell Temperature, and Fill Time.

In this study, the casting from Case Study III was analyzed. For these simulations the gates and risers that were suggested by the foundry were used, as shown in Figure 9, not the modifications that were designed to create a sound casting.

First, the initial pour temperature was varied in the software. Pour temperatures being too low, as defined by the temperature of the metal when it exits the ladle and enters the mold, could result in cold shuts and misruns. Understanding how the thermodynamics affects the fluid dynamics is essential for parts with thin walls, where this may become an issue. The foundry provided the data for their variation in temperature, which was 2876 ±36 °F. When this temperature was increased in the simulation, an increase in porosity was found. However, when this temperature was reduced, no change in porosity was found. The resulting material density plots can be seen in Figure 16.

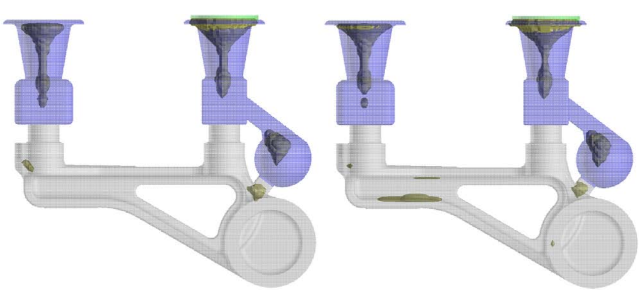

Figure 16: Pour Temperature Variation Results, 2840 °F (Left) and 2912 °F (Right)

Next, the shell temperature was varied. Lower shell temperatures result in accelerated cooling of the metal that flows along the shell surface. Like changes in pour temperatures, shell temperature variation can lead to casting abnormalities and defects. Again, this data was supplied by the foundry at 752 ±36 °F. In this situation an increase in shrinkage was seen in both cases. The results can be seen in Figure 17.

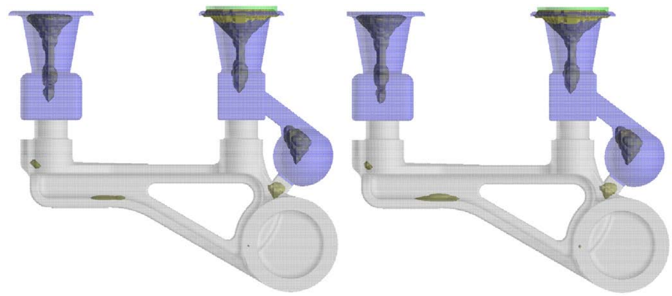

Figure 17: Shell Temperature Variation Results, 716 °F (Left) and 788 °F (Right)

The last parameter examined in this case study using SolidCast was the fill time. If a part is poured excessively fast, mold damage could occur and defects could be caused by the turbulent flow. Changes in flow rate could also cause the metal to solidify in an abnormal fashion, resulting in unforeseen issues. The computer software can calculate the optimal fill time depending on the size of the casting and combined gates and risers. Solidcast calculated the ideal fill time to be 9.4 seconds for this part, which resulted in a flow rate of 8.37 in^3/s. In the foundry, this figure is not always constant, therefore for simulations the fill time was varied by ±20%. The material density plots can be seen below in the following side by side comparison, Figure 18.

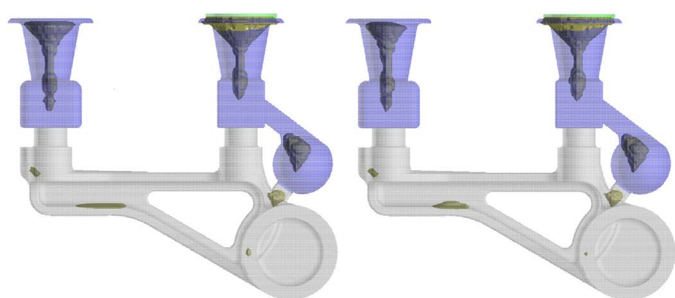

Figure 18: Variation in Pouring Time Results, 7.52s (Left) and 11.28s (Right)

There are many other parameters that were not discussed in this case study that can be simulated using SolidCast. Orientation can vary in real world casting conditions if the shell is slightly tilted from the vertical position during the pour. This is very common due to a large number of molds being buried in sand before they are filled. This may go unnoticed, but affects the fluid dynamics of the pour. Another variable that may have importance to shrinkage formation is the ambient temperature. Substantial variations in ambient temperature can affect the cooling rate of the shell. Mold material properties and heat transfer coefficients can also be adjusted to closely reflect the current casting production run.

Conclusion

Shrinkage in castings can affect the overall strength and fatigue life of the designed part. This creates a need for predicting sound castings in order to reduce lead time and cost. While further research must be done in order to make a claim that casting simulation software can be relied upon to be accurate in every situation, this investigation shows a correlation between computer software simulations and the actual casting process. As shown in Case Study III, accurate results are dependent upon correct evaluation of the initial conditions.

The Critical Fraction Solid Time and Material Density plots in SolidCast can be used to successfully predict shrinkage in castings. Evidence of this can be seen in Case Study I. In this study, the successful simulation results allowed for a quick transition between sampling and production. The computer software can also correctly determine proper feeding zones, as shown in Case Studies II & III. It was also shown through simulation, non destructive testing, and sectioning, that shrinkage can form when these feeding zones are not taken into consideration. With these tools it is possible to create gating systems that would allow for sound castings.

Non destructive testing, including Phased-Array Ultrasonic Testing, was shown to be able to effectively locate shrinkage in these mild steel castings. Inspecting castings in this manner reduces waste and speeds up the detection process. Surface gas porosity was able to be identified by the use of SCRATA comparator plates.

Varying initial conditions showed that substantial changes in solidification can occur while operating within the tolerance of those conditions if the rigging is not robust enough. The initial conditions should be provided by the foundry that produces the parts, and the degree to which the solidification is affected must be examined on a case by case basis. While it is not feasible to test every combination of initial conditions, it is beneficial to understand how each parameter can affect the integrity of the casting. It was found to be difficult to group every initial condition that is possible therefore future simulations should be performed while taking additional initial conditions into account such as the ambient temperature and orientation.

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