Eliminating Shrinkage Porosity in a Complex Investment Casting Part

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ABSTRACT

Shrinkage porosity continues to plague investment casting foundries resulting in costly repairs and in many cases scrapped castings. Reproducing castings that have been scrapped or reworking parts that can be salvaged are not only costly in terms of additional labor and materials needed, but can also be costly in the damaging effects of poor on time delivery. The damaging effects are then compounded if shrinkage remains in the casting and is found during a machining operation or worse, a failure in service. Reducing the number of shrinkage defects can have an enormous impact on the profitability of a product line, and ultimately, on the profitability of the company. Therefore, it is imperative to the Foundry Engineer to develop tree designs that fulfil the quality requirements that the customer requires despite growing casting complexity and expectations. In this paper, a systematic way of identifying the conditions that lead to shrinkage porosity and the methodology employed to eliminating the porosity will be reviewed using a case study of a complex investment cast part.

Introduction

Shrinkage porosity is an issue that every investment caster deals with, but it can be mitigated identifying concerning areas on a part before it enters production. When liquid metal freezes, its density increases and leaves some of the surrounding volume empty. Parts containing these voids can fail to meet customer's quality requirements due to functional or cosmetic issues. Many times these issues are only discovered when a part goes into production. Scrapping castings and re-cutting tooling to resolve the issue can greatly reduce the profit margins on a casting. Thus, following a robust approach to gating castings before they go into production is mandatory. New casting designs should be evaluated by considering one's objectives, defining potential variables, specifying evaluation criteria, and making a plan to compare production metrics of the resulting design to historical numbers. By considering these steps in advance, unforeseen costs can be mitigated and parts can be made with higher profits, lower lead times, and more consistency.

Porosity

The root cause of metal shrinkage is due to changes in the spacing between atoms at the metal cools. In the liquid state, atoms flow freely throughout the melt. At higher temperatures, atoms stay farther apart from each other. As a result, metal is the least dense when it is first pored. While the liquid metal cools, it shrinks slightly, however this has little effect on the final casting. Because the casting is still fully liquid, volume lost due to liquid phase shrink does not form voids.

As metal cools, dendrites begin to grow in liquid metal at the liquidus temperature and the metal completely solidifies when it reaches the solidus temperature. Areas that cool more quickly, such as thin sections and the outer edges of the casting, are the first to solidify. Thick sections of the casting hold a lot of heat and tend to cool last. The first sections to solidify will compensate for their loss of volume by drawing additional liquid metal from the areas around them. The last areas to solidify, however, have no liquid metal in their vicinity and no new metal will fill in the shrunken regions. Thus, shrinkage porosity will form in the last areas to solidify.

Shrinkage porosity is one of the most common issues that foundry engineers address. As liquid metal cools it becomes denser, and this loss of volume can create voids in the final casting. While some level of porosity is acceptable in most castings, if it is not properly addressed it can be detrimental to the functionality or appearance of the finished part. Using a large sprue is a common way of removing shrink from investment castings. Instead of the heavy sections of the casting cooling last, the sacrificial sprue will continue to feed the casting until it fully solidifies. This technique makes use of “directional solidification,” in which the metal in a thin section is fed additional liquid metal by a heavy section, which is in turn fed by the sprue. This technique is dependent on making sure the gates solidify after the casting so they can continue to feed liquid metal to the casting as it cools.

Not all porosity is worth addressing, however. Attempting to remove all porosity from a part typically requires complex and expensive risering, which makes the casting cost-inefficient. Yet shrink occurs in key functional or visually important area on many parts, and it is important to understand how to effectively address this issue.

Approach

Following a robust and repeatable process is the best way to approach issues with porosity in investment casting. A consistent process can help engineers avoid missing key details and produce quality castings on-time for every project. The first step of this process is to determine what requirements the casting needs to fulfil. Then one considers what designs are possible and what process variables can be adjusted. It is also important to determine the criteria by which one will judge whether a design has fulfilled the objective. Viable designs can then be determined and tested to find the optimal version. Finally, one must implement the solution and then confirm that the solution is working as expected.

1. Set Objectives

Considering objectives in advance keep work on-track and make time is applied efficiently. When making design changes, there are two primary objectives: meeting customer requirements and making the job profitable. The “meeting customer requirements” objective means producing parts that will not be rejected by the customer. If the customer does not specify exactly what they need, requesting further information keeps one from addressing criteria that are not necessary to make a good part. Applied to reducing porosity, this could include knowing whether shrink in non-machined regions is acceptable and knowing where the machined sections are.

Job profitability is the second major objective for every new part that comes in. Parts that are made at a loss are best to avoid. However, determining whether a part is profitable or not requires an understanding of internal costs. For instance, how much does every square inch of gate cost to cut and then grind? These prices can be difficult to assess and must be estimated from monthly totals, but can give a better sense of which designs need to be improved.

Part designs must meet both the "customer requirements" objective and the "job profitability" objective to be moved into production.

2. Define Variables

When approaching an objective, listing in advance what variables can be changed will keep all possible options available. If one focuses on solving shrink with gating alone, one may lose sight of opportunities to mitigate the issue by changing pouring temperature, changing shell temperature, or adjusting shelling parameters. Additionally, depending on the part and customer, key changes can sometimes be made to the casting design. Adding feed paths, thickening thin areas, or increasing radii can make it far easier to address shrink in difficult features.

Considering what you cannot adjust can also provide valuable constraints for your design. Noting the part orientation required to water blast off shell or where wax would be unable to drain will prevent the creation of new problems while addressing a shrink issue. Having a good sense of constraints and variables before starting a project allows one to consider and compare multiple potential solutions and to be confident that the best solution was reached.

Variables should not be eliminated at this step. Even variables that failed to work on other projects, such as risers, may be valuable to consider and should not be struck from the list.

3. Specify Criteria

Developing evaluation criteria is a way to judge whether the objective has been completed. Criteria should be related to the objectives and measurable. For instance, an objective that states "improve job profitability" could produce the measureable criteria "reduce scrap below 2%" or "reduce weld repair to 5% of parts." Properly defined criteria are used to determine when a gating design for a new part is finished or when a continuous improvement project is complete. Setting a specified end point lets engineers know when to apply their time to a more pressing project.

4. Keep the Task Efficient

An engineer should always seek to reach the best design in the least amount of time. Time spent working on a gating design that turns out not be successful is lost time. To avoid going down a rabbit hole, a few separate ideas should be considered for nearly every project. The exception to this may be a low production or one-off part, where extra designs would be unhelpful. For high production parts, considering more possibilities may save valuable time and resources in the long run.

To gate higher production parts, one may take a few approaches to creating new types of designs. For instance, three different types of sprue could be considered, each with a different idea for gating design. Additionally, one gate, two gate, and three gate designs could be made. Another part may be approached by choosing multiple orientations and gating in accordingly. These changes each involve a few types of designs to be considered, but the exact sizes of gates are left until further into the design process to be defined. For now, the engineer is simply concerned with creating a few different methods to reach the same aim.

The goal of this step is not to create finished designs, but to come up with more than one way to meet the criteria. This way, the best of multiple designs can be chosen for further revision instead of spending time trying to make a bad design work.

5. Choose a Method

Choosing a sampling plan should be based off of the part's production rate and the number of designs that seem worth investigating.

Determining the number of sample designs to be run is a key part of creating a sampling plan. When sampling for a low production run part, one design for sampling and PPAP may be best. Trying one large gate size may be enough to ensure that scrap is eliminated without wasting resources on sampling. For a larger production part, a larger number of samples allows an engineer to try a variety of gate sizes to optimize yield while still feeding shrink. Sampling is expensive, but becomes more worthwhile on high volume parts where a small design change could save a lot of money.

When using simulation software, many designs can be evaluated without the expense of sampling. The simulations still take time to run, and while their contribution to lead times are shorter, a well-developed project plan can reduce the number of simulations required to meet the objective. Even with simulation, at least one sample must be run of the final design for PPAP and more may be required to hone in process variables. Thus, considering objectives and variables in advance can reduce lead times, reduce sampling costs, and produce high profit castings.

When the sampling or simulating is finished, if the design meets the required criteria, the tooling is ready to be cut.

6. Act and Check Improvements

Once the best design is chosen and put into production, tracking the success of the project can begin. Projects should be monitored for scrap and hold-ups in production as well as customer returns to determine whether the design needs to be revaluated. For projects that addressed an issue with previous production, comparisons can be drawn between new and previous data to justify the improvement. In the case that the new parts are worse than the past design, the design can be reverted back while another solution is tried. Tracking the success of projects determines whether an engineer's work is complete.

Case Study

1. Set Objectives

A stainless steel valve component produced by Eagle Precision, shown in Figure 1, has had a long history of rework. The part is roughly cylindrical with one open end that has four mounting tabs and one closed end that gets drilled by the customer, show in Figure 2. One side of the part has a ribbed arm that protrudes from the body. 75% of the parts require weld repair at the base of the arm due to visible surface shrink (Figure 3). About 800-900 parts are run per year, each costing $10-12 in weld repair for a total of $8,000-$10,000 in lost revenue annually. Eagle Precision approached MAGMA to assist in eliminating the surface porosity.

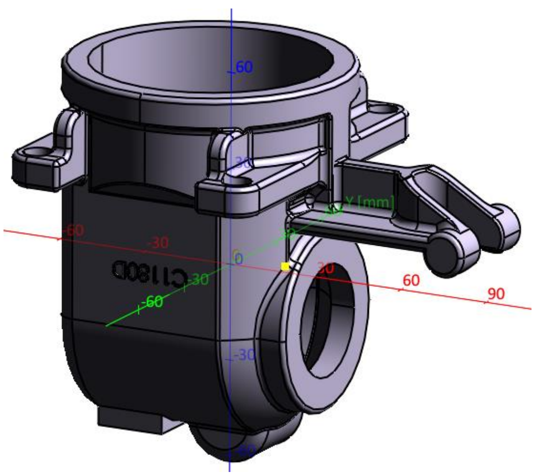

Figure 1. A CAD model of the Eagle Precision part.

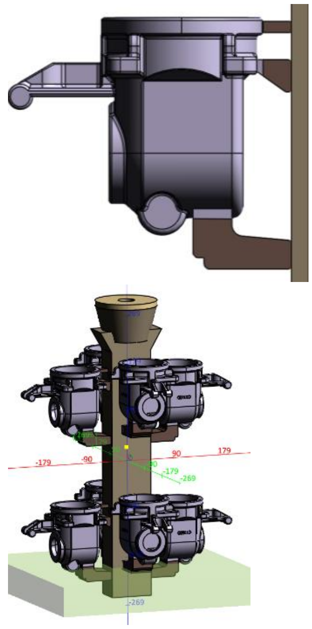

Figure 2. CAD Models of the original gating and assembled sprue.

Figure 3. Welded shrink at the base of the arm.

While the presented goal is to remove the surface porosity and eliminate weld repair, cost is also a major concern. Shrinkage porosity is not hard to remove, but it is hard to remove in a cost-effective way. In the case of this OEM, the casting may have internal shrink but not visible eternal shrink in any locations, as well as be free of shrink in machined locations. These requirements are less expensive to address than a stringent X-ray requirement, which demonstrates the importance of fully understanding customer requirements. Thus, our solution should maintain the current levels of subsurface porosity to remain cost effective while not creating any new surface shrink. Considering these objectives in advance ensures that the solution addresses the underlying goals of the project.

2. Define Variables

Once the objectives are determined, the potential variables that can be defined. The primary way to address porosity in investment castings is by changing gating design. Within gating modifications, one can alter the shape, size, and number of gates, as well as the gate location and part orientation. There are also the options of adding new features such as preformed holes or blind risers. In this case, the OEM is open to design changes which allows for minor modifications to the part such as adding feed paths or thickening sections. To avoid causing the OEM to reject the design changes, one must avoid interfering with tool paths or requiring additional machining time. Sorting through these variables provides many ideas for potential new designs.

3. Specify Criteria

Setting up evaluation criteria in advance allows one to evaluate whether the new designs fulfill the set objectives. To approach our objective of eliminating surface porosity, our criteria is to reduce weld repair below 10% at the base of the arm. To accomplish this we must have little to no internal porosity. Our second objective, to reduce costs, has many factors that makes it harder to quantify. To meet this goal, yield, grinding time, and subsurface porosity (shown in Figure 4) need to remain relatively constant to ensure that no new issues are created. The final design must meet all of these criteria to be a recognizable improvement over the current gating.

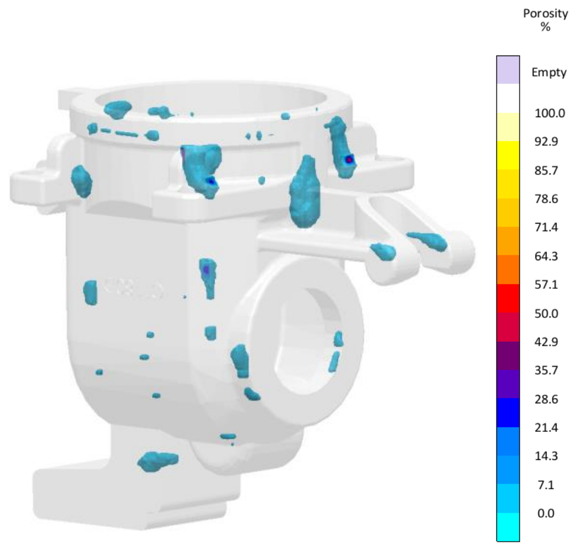

Figure 4. The porosity simulation result for the current gating. The scale shows the percent density of the porosity.

4. Keep the Task Efficient

Considering how the defined variables can be combined to fulfill our criteria keeps the project on track and reduces the number of simulations that need to be run. While it is much less expensive to run simulations than it is to run samples, simulating an excessive number of unlikely designs is not time effective.

A few general approaches to gating were developed based on different part orientations. Each orientation was intended to keep as many hot spots as possible close to the sprue. These designs will be tested in a design of experiments that tests each design independently with varied gate and riser sizes.

The orientation-based approaches are as follows: The first design (Figure 5) consisted of a tilted casting with three gates, one of which reached close to the base of the arm and was connected with a minor feed path. The second design (Figure 6) uses large risers tied back to the sprue to feed hot spots in the bolt tabs and at the base of the arm. This variant requires a large metal addition to the arm, raising the weight of the casing by 0.1 lb but considerably improves the feeding. A large gate on the bottom of the casting feeds a hot spot in a machined area. The third design (Figure 7) is gated into the same arm addition, but base of the casting is oriented towards the sprue. The design uses a spherical blind riser to address the heavy machined section, in an effort to avoid potential shrink. The fourth design (Figure 8) uses the same arm addition and part orientation as the third design, but instead has the hole in the heavy section preformed. Each of these designs appears viable before testing, and are reasonable to sample or simulate.

Figure 5. CAD model of design variation 1.

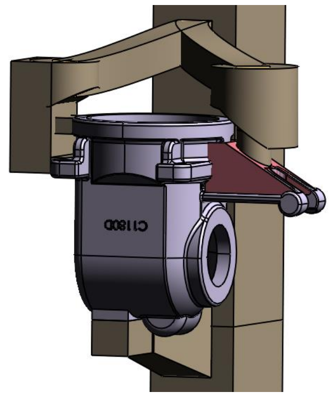

Figure 6. CAD model of design variation 2.

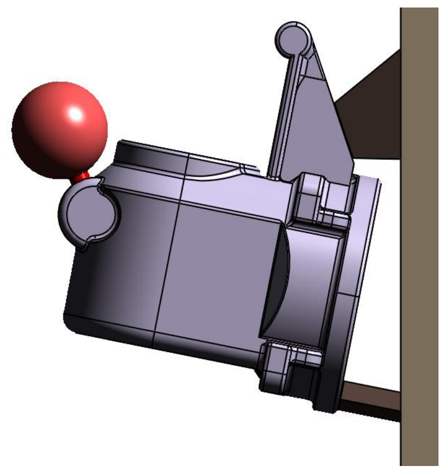

Figure 7. CAD model of design variation 3.

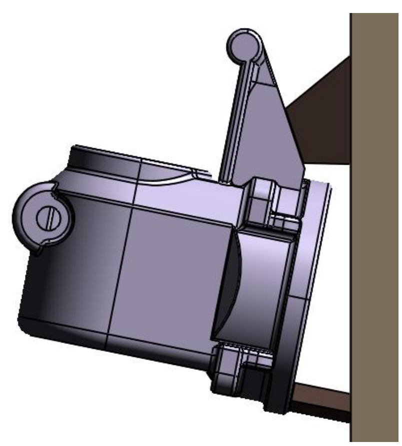

Figure 8. CAD model of design variation 4.

5. Choose a Method

Each part orientation was tested in a separate full factorial design to optimize the sizing of gates and risers. Because simulation is relatively inexpensive to run and a fair number of parts are to be produced, enough variations of gate and riser sizes were tried in order to find the optimal combination. Once the best version of each design was decided on, they could be compared.

After the designs were simulated (or potentially sampled), they were inspected to see if they met the established criteria. First, porosity at the base of the arm was examined via simulation, but alternately the cross section of a sample could have been cut and polished. All of the designs successfully eliminated shrinkage porosity at the base of the arm.

The parts were then be scrutinized to see if yield, grinding time, and subsurface porosity are better or equivalent to parts produced by the original gating design. Design 1 showed concerning levels of porosity in the mounting tabs (Figure 9), and while the original design had minor porosity, the new design may have issues under process variation. Gate grind was also found to be an issue, as a small overhang on the arm prevented proper grinding of the center gate.

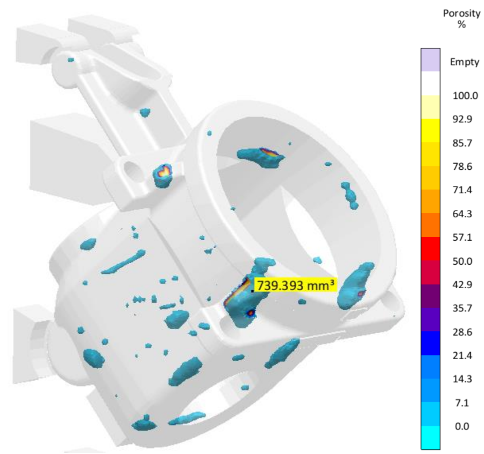

Figure 9. The simulated porosity of design variation 1 in percent density. A 740 mm^3 volume of subsurface porosity is predicted in one of the mounting tabs far from the sprue.

Design 2 had great results for porosity, but the yield was only 30% compared to 38% yield for the original gating, and therefor is likely not the best design.

Design 3 successfully uses the blind riser to avoid problematic porosity in the heavy section (Figure 10) while meeting the same yield as the original gating. Design 4 uses the preformed hole to shift porosity away from the machined section (Figure 11), although it may not survive the process variation inherent in production. Designs 3 and 4 meet the set criteria more effectively than the others, and were set aside for sampling.

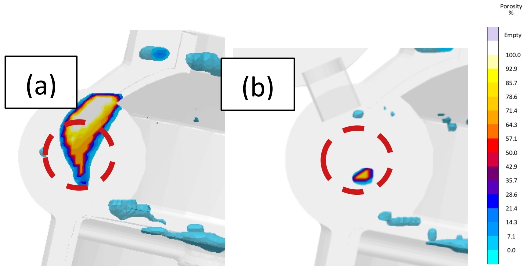

Figure 10. The simulated porosity of (a) the current gating and (b) design variation 3 in percent density. The porosity is mostly eliminated from the drilled hole by a riser in variation 3.

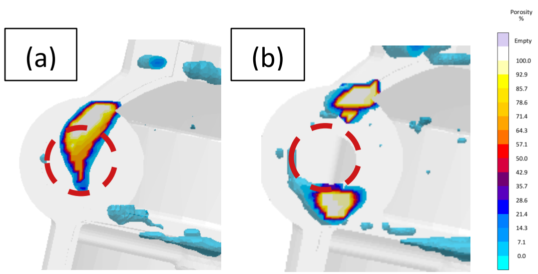

Figure 11. The simulated porosity of (a) the current gating and (b) design variation 4 in percent density. The porosity is moved somewhat away from the drilled hole by preforming the hole in variation 4.

6. Act and Check Improvements

While the project has not yet progressed beyond this point, the two designs are expected to finish sampling soon. From there one final design will be chosen based on whether riser is worthwhile for eliminating shrink compared to the improved yield of the preformed hole version. When the final design is put into production, data will be gathered to see how successful the project truly was and the cost savings will be quantified.

Concluding Remarks

Whether approaching a high-scrap production part or a new job, it is important to follow a set approach. One should set objectives, define variables, set criteria, keep their task efficient, choose their method, and act and check the improvements. Each step helps produce better designs and test them with fewer sampling runs or simulations. By following this process, the engineer can become more efficient in their design process and reach optimal designs faster.