Increasing Profitability with Yield Savings using Autonomous DoE

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ABSTRACT

Traditionally, the investment casting foundry engineer has had the primary goal of designing tooling that maximizes quality. However, foundries are being challenged more than ever to provide high-quality castings at the lowest possible cost to the casting buyer. Remaining competitive in this type of environment requires developing manufacturing processes for new and existing jobs that minimizes the overall production cost. While the use of casting process simulation has aided the engineer with the task of producing a sound casting, simulation has not customarily been used to consider the costs related to producing the casting using the tooling that has been designed. This paper highlights a case study that utilized material, labor, and production cost with a focus on yield, which was integrated into the casting process simulation software interface. Having the costs associated with producing the casting with varying tooling designs, along with the predicted quality level of each design, gives the foundry engineer a much better idea of the actual overall cost associated with producing the casting.

Introduction

When designing gating systems, the primary objective is often quality. With the risk associated with first-time-run jobs and the propensity for certain alloys to form porosity and misrun defects, it is in the foundries best interest to focus on increasing first pass yield and eliminating defects. The use of casting process simulation tools has aided engineers in designing robust gating systems that improve the quality of castings, but often the cost of the gating system isn't considered during development. The question then becomes, are the castings that are being produced with the highest possible quality at the lowest possible cost? This question will be explored using yield, which is one component of casting cost.

What is yield?

Yield is the ratio of the casting weight and the pouring weight, which is typically given in percentage. It is often thought of as how efficient the casting system is. To ensure casting soundness a volume or volumes of liquid metal must supply the casting with feed material as it cools and contracts to avoid shrinkage defects. As a result, excess metal must be melted that will not be sold to the customer after the production process has completed. This extra metal can be removed from the casting and re-melted, but this does not come without a cost. Melt loss and energy cost must be accounted for in the evaluation of a gating system design to determine if a design chosen is the most cost-effective.

Melt loss

During melting, pouring, cut-off, and grinding processes, alloy material losses accumulate. The losses that accumulate during the casting process must be replaced with new material, which is why there is a cost associated with performing those operations. Melting contributes to the material loss primarily through oxidation. When metal encounters oxygen during melting, the material oxidizes and forms what is known as slag. The newly formed slag, if left in the metal, will be both destructive to the properties of the material and to the physical appearance of the casting. Because of this, slag is removed from the melt during the melting process. The slag contains alloying elements that will need to be re-purchased later. The more losses that accumulate due to oxidation, the more alloying content that will need to be added to the furnace during melting, the more inventory is used up.

When castings are cut off using a cutting wheel, torch or other means, material is lost. How much material is lost depends on the cutting method used. Because that material is not recoverable, it is another source of the cost associated with producing a casting. Similarly, when gate contacts are ground, the material is lost. Cut off operators attempt to cut as close to the casting as possible, but it is unlikely that the operator will be able to cut off the gates so that there is no excess material on the casting. Grinding this excess material off to produce the finished shape of the as-cast surfaces of the casting will eliminate that material. The total of the material losses accumulated during the casting process can be approximated at 5% – 8%.

Energy cost

The ability to recycle metal through many cycles is a critical component in keeping the cost of castings down. Instead of cutting off the excess material needed to produce a casting and disposing of it, the extra material is re-melted and used again. The critical thing to consider, however, is that it takes energy to melt metal and that energy has a cost which is expressed in $/lb. Energy cost can vary depending on location and type of melting process. Induction furnaces that are small to medium size can have average energy cost from $0.026/lb – to $0.06/lb.

Capacity

One subject matter that is worth mentioning, but is very, very difficult to quantify would be the capacity gains realized by increasing yield. When it takes less metal to melt the same amount of parts, it can have an impact on scheduling, labor, and potentially the ability to take on new customer work. To see how yield might impact scheduling, we will turn to an example. Suppose you have one 250lb furnace and you want to pour five 25lb castings. If the yield is 50% and you neglect melt loss, you can melt and pour metal for all 5 castings in one heat. If the yield is 35% however, you will need to melt two heats to pour the same amount of castings. One can infer from this that if it takes fewer heats to make its current product mix by increasing yield, it is possible that those vacant heats can be supplanted by new additional work. As mentioned prior, this line of thinking is difficult to quantify but should be considered when making decisions on whether to take on yield improvement projects.

Yield cost saving calculations

To be able to quantify savings realized by making some improvement to yield, we must first put the various cost mentioned above in numerical form and calculate the differences between the two scenarios. The three main components that will be used in the calculation are material cost, labor cost, and overhead (O.H.). For these calculations, environmental cost is ignored for simplicity; however, it should be considered when doing these calculations in the foundry. A detailed description of the breakdown of each cost components will not be discussed, but the foundry running a cost analysis should have the appropriate values for those items mentioned and will vary from foundry to foundry. One important thing to note is that cost associated with melting is typically converted into a $/lb unit. So material cost, labor cost, and O.H. will be given as a price per pound value. Also, the energy cost is accounted for in the O.H. cost. So the first thing to do is calculate the total amount of metal that should be consider in the calculation which is a function of the casting weight, yield, and melt loss. That relationship is given by Equation 1.

$$W_t = W_c * [1/Y] * [1/(1-ML)] \qquad (1)$$

Where $\mathbf{W_t}$ is the total weight, $\mathbf{W_c}$ is the casting weight, **Y** is the yield, and **ML** is the melt loss.

For now, we are going to assume a 0% scrap rate; however, if a scrap rate is known for a particular part number, it must be taking into account in the calculation. Now, after the total weight is calculated, the return weight or the weight of the tree and gates must be calculated. That relationship is given in Equation 2.

$$W_r = W_c * [(1-Y)/Y] \qquad (2)$$

Where $\mathbf{W_r}$ is the return weight, $\mathbf{W_c}$ is the casting weight, and **Y** is the yield. It can be that the returns are integrated into the material price, however, in this example, the returns are treated as a credit to inventory at half the value of the initial material cost. Let's explore two scenarios for casting with two different yield values to demonstrate the calculation.

Suppose that in scenario 1 the casting weight is 25lbs, the yield is 35%, and let's assume that there is one casting per tree for simplicity. In scenario 2 the yield will be improved to 50%. Material cost, labor cost, and O.H. cost will be given as $2.00/lb, 0.05/lb, and 0.06/lb respectively. Melt loss will be 7%. The calculation will follow as:

Scenario 1

W_t = 25.0lb * [1/0.35] *[1/(1-0.07)] = 76.8lbs
W_r = 25.0lbs * [(1-.35)/.35] = 46.4lbs

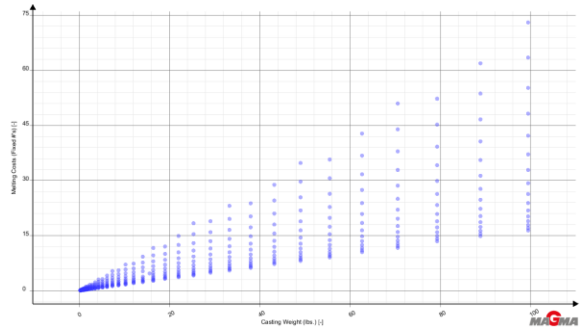
Total cost = 76.8lbs * [$2.00/lb + $0.05/lb + $0.06/lb] – [46.4lbs * $1.00/lb] = **$115.65**

Scenario 2

W_t = 25.0lb * [1/0.5] *[1/(1-0.07)] = 53.8lbs
W_r = 25.0lbs * [(1-0.5)/0.5] = 25.0lbs

Total cost = 53.8lbs * [$2.00/lb + $0.05/lb + $0.06/lb] – [25lbs * $1.00/lb] = **$88.52**

The difference in cost in the two scenarios is $115.65 - $88.52 or $27.13. One important thing to note while performing yield savings calculations is that material cost can vary greatly. Materials that are more expensive such as stainless steels and nickel-based materials can potentially have higher cost differences than materials such as carbon steel or iron. Another critical thing to consider is that the casting weight is also a major contributing factor. As the casting weight decreases, the melting cost also decreases. If different castings weights of different yields are plotted on a graph, an interesting trend emerges (Graph 1). The spread of melting cost associated with a casting weight gets larger as the casting weight increases. This means that the larger the casting weight, the larger the potential for savings. Each dot represents a scenario, while the y-axis is melting cost and the x-axis is casting weight.



Graph 1. *The relationship between melting cost and casting weight*

Costing integration with casting process simulation

Calculating the potential cost impact of yield for each design that the foundry engineer considers can be time-consuming if done manually. The preferred approach would be to have the casting process simulation tool used by the foundry engineer to have the cost associated which each design included in the output of the optimization. Integrating cost information with Autonomous DoE allows the engineer to not only consider the impact on varying tree and gate designs on the quality of the part but also considers the cost of each design so that the engineer can make better decisions on which potential setup to select. For example, if two designs provide the same quality, whether the objective is to eliminate shrinkage, misrun, etc., then the cost of the two designs could be used to determine which to send to production. The first step to integrating cost with Autonomous DoE is to create a costing model that captures the expenses accumulated during the casting process. This model can be both constructed first in a spreadsheet (Figure 1) and then transferred into the software, or it can be developed in the software itself.

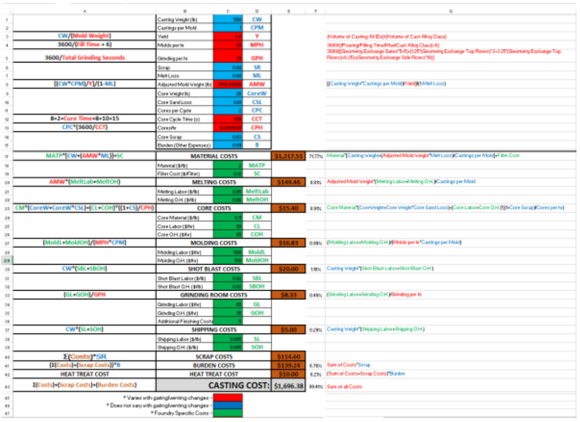


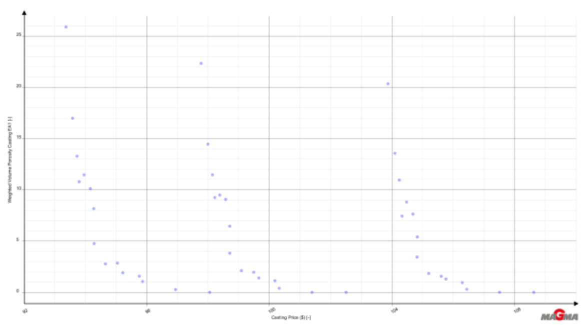
Figure 1. *Spreadsheet model used to perform cost calculations*

The quoting department likely has this information available so that the foundry engineer doesn't have to collect the data themselves. The casting process simulation software will consider the cost of a design using an objective (Figure 2).

Figure 2. *A cost objective has the relevant costing equations derived from the spreadsheet model*

There will be a mix of fixed and variable cost included in the calculations. The key here is for the foundry engineer to identify the variables or things they can change (various design possibilities), in the simulation that will affect the objective, which is casting cost. For example, the variable that is used to consider the melting cost is the casting weight and the pouring weight. So as different design configurations are evaluated with different yield values, the resulting cost associated with the change in the designs will have a corresponding cost. A good first step would be to have the cost information available to the engineer so that they can make better decisions for which designs to pursue. However, the goal can be to use the cost objective to find the best compromise between casting quality and manufacturing cost. Casting quality is by far the number one concern for foundries. However, there may be some cases where the customers quality criteria allow some internal defects, which could provide an opportunity to the foundry to focus on minimizing casting cost instead of maximizing casting quality.

After the Autonomous DoE has been run and you have multiple designs to evaluate using quality objectives such as porosity, as well as cost objectives such as casting price, we can explore different ways of visualizing the data generated by running the simulation. One way of visualizing the data is with a scatter plot (Graph 2) where each dot represents a design that has been run, while the y-axis is porosity and the x-axis is the casting cost which includes yield.



Graph 2. *Shows the effect of porosity on casting cost*

The simulation shows many designs that have zero porosity but at different casting prices. By looking at this snapshot, one can conclude that the designs in the lower left should be chosen even though there are designs to the lower right that have zero porosity. Considering the cost of the design allows the engineer to both consider quality objectives such as porosity and cost objectives such as casting cost.

Case Study

Conbraco Industries Inc., an Aalberts Industries company, Steel Products Division, operates a 170,000 square foot airset and investment foundry in Conway, SC. The fully captive foundry outputs roughly 3 million lbs of castings yearly, enabling Conbraco to produce the Apollo Valve is a fully USA manufactured product; cast, machined, assembled, and tested in South Carolina.

Project Inception

Part number U1523040, a 3" NPT valve body casting, was initially gated using an existing tree in 2012 without using casting process simulation. Orders for the component from 2012 to 2017 never exceeded 100 pcs per year. In 2018, a customer approached the foundry to order 12,000 pcs per year at a rate of 1,000 pcs per month. The foundry manager tasked the manufacturing engineering team to develop a more efficient production method. The original setup (Figure 3) was gated 2 per tree using an existing investment tree. The setup weighed 107.6lbs with a yield of 26%.

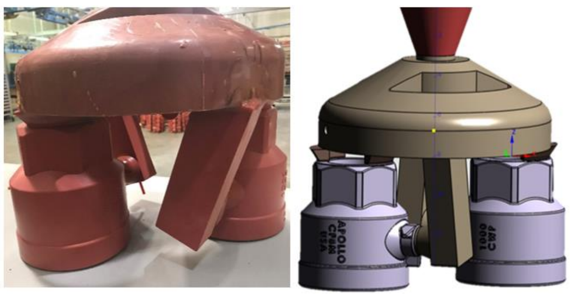


Figure 3. *Wax assembly (left) and simulation model (right) of the existing setup*

To come up with a solution, Conbraco used casting process simulation to test their ideas to come up with solutions before running casting trials. Pouring dozens of sample castings with different gating systems is not practical, so using a virtual environment to help inspire creative and innovative solutions is much more practical. After several iterations using manual optimization, two new potential setups were chosen for analysis (Figure 4, Figure 5).

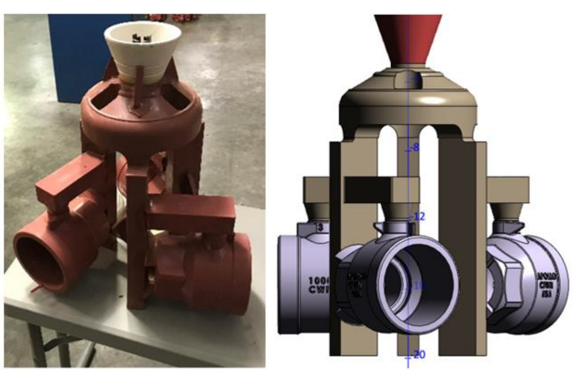


Figure 4. *Wax assembly (left) and simulation model (right) of the intermediate setup*

Figure 5. *Wax assembly (left) and simulation model (right) of the final setup*

The design termed the intermediate setup was run using a standard tree setup used by Conbraco on many of their parts. A third casting was added, and the yield improved to 33% with a total tree weight of 125.2lbs. A seven percent improvement was significant, but it wasn't entirely clear if it would be enough to justify the expense of changing the setup. The domed setup that has been used for years and years was then brought into question. Out of necessity due to cut off constraints, the domed tree design was standard. However, the project scope allowed for the removal of this constraint to see what was possible. Changing the tree design and adding an extra casting had the potential to increase the yield to 49% for this part number. The three designs were placed in a single simulation setup, and the Autonomous DoE tool available in casting process simulation was able to cycle through each design and run the simulations without further intervention from the engineer. After the simulation was completed, the three designs could be evaluated simultaneously in a single version. First, the quality of new design configurations were compared to the baseline using results such as Hot Spot FSTime (Figure 6) which shows the time in seconds it takes for a region of the casting system to become cut off from feeding.

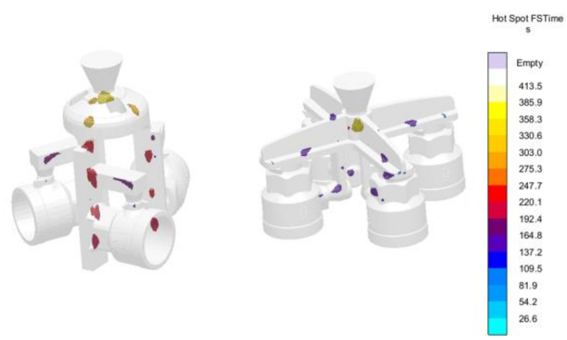


Figure 6. *The quality of the two selected designs were comparable to the baseline simulation*

After it was determined that the quality of the new designs was comparable to the baseline system the cost associated with each design was evaluated. The difference between the baseline simulation and the final design was calculated by the software to be $77,574.43 in potential savings. The first years cost, simulation time, tooling change, change in setup, etc., will have to be deducted from the total to determine year 1 savings, but if the production rate continues, the savings will accumulate over time.

Conclusion

Using the capability to autonomously run virtual designs of experiments optimizations with integrated cost calculating objectives available in casting process simulation will allow the engineer to look at both the quality performance of the tool design, but also consider the cost of each design before the tool is set to production. Existing jobs that can benefit from yield improvements can also be examined to find the new tree and gate designs that will reduce the melting cost associated with casting the production part. It is important to note that the expense of tooling changes and other added cost must be considered and subtracted from the potential gains.