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Generative Gating Method and Case Study

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ABSTRACT

This study presents a novel method for generating gating systems directly from metalcasting process simulation results. Traditionally, skilled engineers design gating systems using computer-aided design (CAD) software, relying on established calculations and geometric features. While simulation software verifies runner performance and allows for adjustments, the design process can be labor intensive. Here, we propose a "Generative Gating Methodology" that leverages simulation data to automate gating design. The objective of generative gating is to produce effective runner systems that can be produced quickly and by engineers with less experience in gating design. This methodology is applied to a real-world casting scenario, replacing the existing gating system with an automatically generated design. Casting samples produced using both approaches are evaluated and compared for quality. Finally, the advantages and limitations of the proposed gating generation method are discussed.

Keywords: generative gating methodology, runners, gating, simulation, generating, computational fluid dynamics, CFD, case study

INTRODUCTION

Controlling the movement of molten metal through the mold has been shown to be beneficial in avoiding defects during casting a range of alloys.[1] Typically, molds are produced with runner systems that are designed to minimize turbulence, minimize velocity, and maintain the high temperature of the molten metal.

Runner systems that minimize turbulence and minimize the velocity of the metal entering the casting cavity have been shown to reduce reoxidation inclusions, which form within the mold as metal is exposed to oxygen.[2] Slow, non-turbulent flow can allow slag inclusions (that enter the mold from the ladle) to be filtered by runners before entering the casting cavity.[3] Slow, non-turbulent flow can also prevent air pockets or dead zones from forming in the runner. These dead zones are low velocity regions that can allow air pockets to continuously mix with metal, creating reoxidation inclusions that may enter the casting.[4] These air pockets can also dissolve gases in the molten metal, increasing the risk for gas porosity defects in some alloys. Avoiding dead zones reduces the risk of inclusions in the resulting casting.

While reducing the metal velocity as it fills the mold typically reduces turbulence, engineers also need to minimize temperature loss while delivering molten metal to the casting cavity. It is critical for metal to fill the casting cavity before it cools below the liquidus temperature, or there may be a risk of cold metal defects. Less temperature loss during filling also allows for a lower pouring temperature, which can reduce slag and melt loss, reduce sand burn-on defects, and increase the life of the furnace and ladle linings. For each pattern, the engineer must strike a balance between slow, controlled filling and filling fast enough to minimize the temperature loss.

It is common practice for many foundries to use metalcasting simulation software to design and test runner systems. Simulation software can predict metal flow and identify locations that may have sustained air pockets as the mold fills. Similarly, casting process simulation also predicts the temperature of the metal front as it reaches the casting cavity. Typically, a foundry engineer will use calculations based on the casting weight and geometry to design a runner system in CAD. They then simulate the system and make changes to the runner system until the simulation predicts a minimal risk of defects in the final part.

NOVEL GATING DESIGN METHOD

A method of automatically generating runner systems from simulation results has been developed, known as the "Generative Gating Methodology.” The steps are as follows:

- **Enter inputs**, specifically the sprue location and dimensions, gate locations and dimensions, and a volume that defines where runners are allowed to be built.
- Run a basic **steady-state simulation** to quickly produce velocity fields. Then filter out the low velocity volumes and export the remaining geometry.
- Import geometry into a **standard simulation**. Run the simulation, filter out the low velocity volumes, and export the remaining geometry.
- Import the geometry into a new, **standard simulation**. Run the simulation to verify quality.

Generative Gating Methodology has the potential to save engineers time when designing runner systems and allow less skilled engineers to design high-quality runner systems. Further research may lead to generated runner systems that can potentially outperform human designed runner systems.

PROCEDURE

The Generative Gating Methodology consists of two phases; a steady-state velocity simulation and a standard filling simulation. The steady-state simulation allows velocity result to be generated quickly, providing an excellent starting point. The standard simulation is run second, and includes additional relevant process information, such as filters.

To begin the process, some starting inputs are required. First, the casting cavities and accompanying risers are positioned on the parting line and a sprue location is selected (Figure 1A). Then a starting area is chosen for the base of the sprue, which may be driven by the manufacturing process (such as an automatic molding machine) or selected based on a sprue choke calculation. Gates are then placed on the casting at feasible locations (Figure 1B). They should be designed such that the combined cross-sectional area of the gates is equal to the cross-sectional area of the sprue choke.

Finally, a volume is drawn that runners are allowed to be built in (Figure 1C). This volume should avoid going too close to the castings or edge of the mold, avoid any mold locks, and follow any complex parting lines.

The thickness of the volume has an influence on the final generated design, which will be discussed further in the Results & Discussion.

The steady-state velocity simulation quickly creates a starting point for future simulations to build upon. The steady-state simulation used in this study is not publicly available but allows the user to place inflows and outflows to quickly reach steady-state flow. The castings, sprue, and runner volumes are set so that flow through them is calculated. An inflow should be placed at the base of the sprue, matching its diameter. Outflows should be placed at a central point on each casting, matching the total cross-sectional area of its gates. The simulation can then be run.

Once the simulation is completed, it will produce a steady-state velocity field result, shown in Figure 2A. The velocity field is then processed by filtering out any velocity values below a certain critical value, shown in Figure 2B. Critical values are currently chosen arbitrarily, and further research is required to develop selection guidelines. Once the low velocity locations are removed, only the high flow-rate volume remains. This is the volume through which the bulk of the metal flows. The high velocity volume is then exported. Depending on the resulting quality of the model, additional processing may be required to produce a water-tight model that is ready for further use.

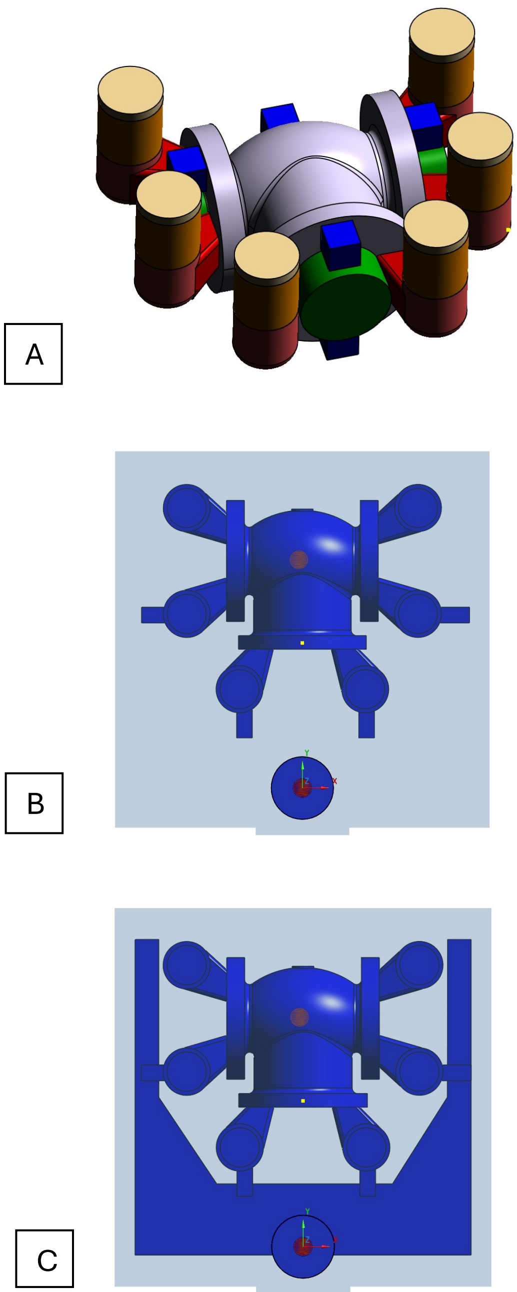


Figure 1. A) Risers and chills are applied to an example casting. B) The risers and casting are prepared for the steady-state simulation with gates and sprue added. A red inflow is placed on the pouring cup and an outflow is placed on the casting. C) A volume is drawn that outlines where runners are allowed to be built.

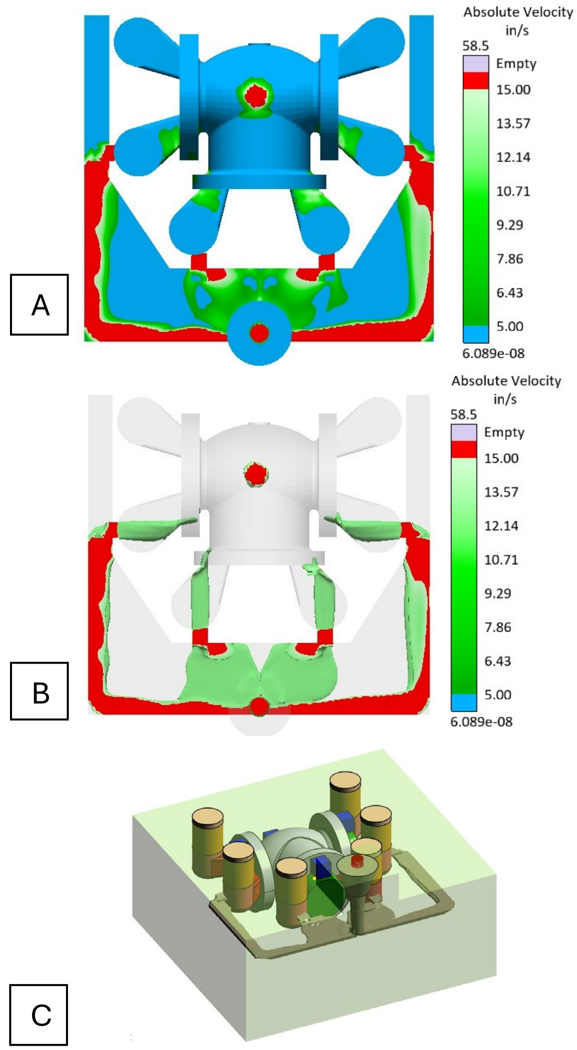


Figure 2. A) The velocities calculated during the steady state simulation, with a scale showing velocities above 15 in/s in red, velocities below 5 in/s in blue, and in-between velocities in green. B) The velocity profile is filtered to show only velocities above 12 in/s, for the model to be exported. C) The model of velocities below 12 in/s is imported into a standard simulation setup.

In the second phase of the method, the model from the steady-state simulation is imported into a standard filling simulation, shown in Figure 2C. Here, further process information can be considered such as filters, pouring rate, and pouring location. The simulation should be set up as realistically as possible. The simulation is then run (Figure 3), and the results are processed similarly: velocities are viewed at a time when the filling is at approximately steady state (typically when cavities and risers are filled evenly and to a metal level that is above the runner system), as shown in Figure 4A. Low velocities are filtered out (Figure 4B), and the model is exported and post-processed to create a watertight model. The model resulting from phase two of the method may be used directly (if the generated design happens to have draft, or in a 3D printed mold application), it may be modified to have parting line draft, or it may be reimported back into the simulation for additional iterations of phase two.

A simulation of the final generated runner is then run and examined in detail, as any other filling simulation would be examined. The engineer should pay close attention to ensure that the temperature is high enough to successfully fill the casting cavities, that there is minimal risk of mold erosion, entrapped air is minimal, and that the entrance into the casting cavity minimizes the surface area of the metal. If the design performs well, it can proceed to tooling. If the design does not perform well, the method may have to be performed again with a new set of inputs. The Generative Gating Method is not entirely subtractive, i.e., it does not only make the runners smaller. A unique element of the solidification software used is that exported models that touch the mold wall will grow one mesh cell larger in that direction (0.1 inches in the case study). This allows further iterations to grow beyond their original boundaries where the metal is being constrained. Additional blockers were required to prevent the runner from leaving the allowable area, but the metal was allowed additional freedom during subsequent iterations. However, this also gives the runners a rough, blocky surface.

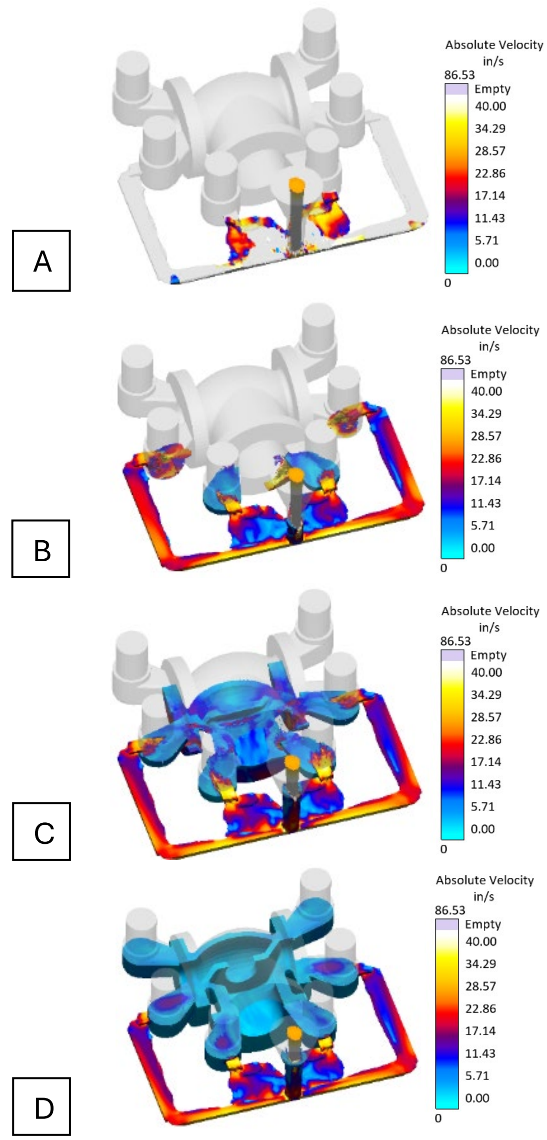


Figure 3. The velocity result as the example casting is filled. A) Velocity at 0.4 seconds. B) Velocity at 1.7 seconds. C) Velocity at 5.0 seconds. D) Velocity at 10 seconds.

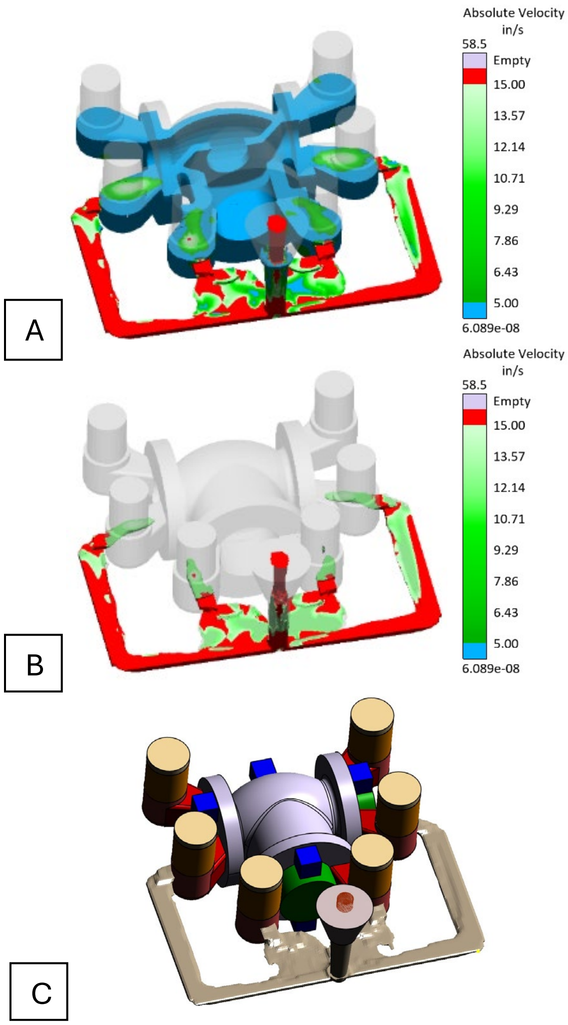


Figure 4. A) The velocity profile in the example casting at 10 seconds, with a scale showing velocities above 15 in/s in red, velocities below 5 in/s in blue, and in-between velocities in green. B) The velocity profile in the example casting at 10 seconds, filtered to show velocities above 12 in/s. The model is ready for export. C)The resulting runner system imported into a new simulation.

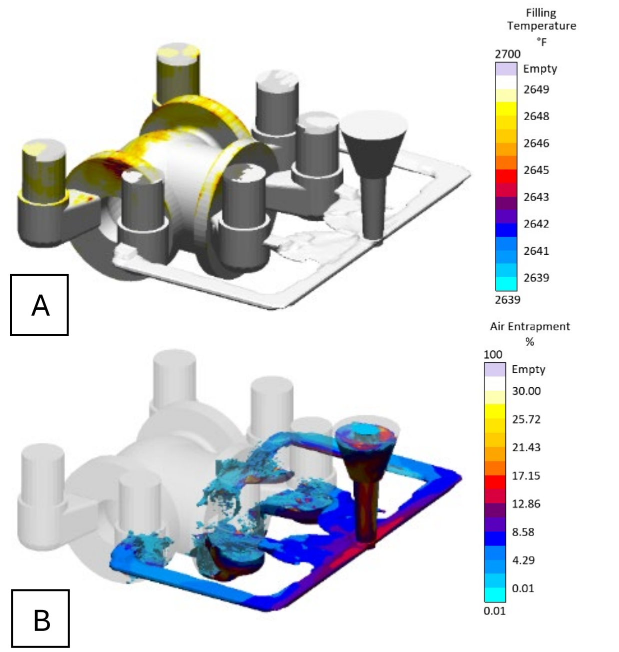


Figure 5. Simulation results for the example castings with a generated gating system. A) The filling temperature result, showing the temperature of the melt front when it first reached each location. The scale shows 10°F (5.56°C) below the liquidus temperature up to the liquidus temperature. B) The air entrapment result, which shows the percentage of air that is mixed into the metal by volume.

CASE STUDY

A gray iron casting with an established quality history was selected to test the Generative Gating Methodology as a proof of concept, where sample castings were poured at a high production iron foundry. The selected casting is run on a horizontally-parted automatic molding machine and poured with a lip-pour ladle. The current pattern design has a central straight sprue, a 20 ppi extruded filter at the base of the sprue, and six casting cavities, each with a hot riser for feeding (Figure 6). The castings require a complex parting line, and the current runners are built in the space between the sprue and the offset parting line. The original pour weight was approximately 194 lbs., and the combined casting weight was 85 lbs. A baseline simulation of the existing pattern and process conditions was run for future comparisons.

With the current runners, the pattern produces minimal scrap. Over the past two years, approximately 1,700 castings were poured. Only 50 castings were scrapped due to possible pouring related defects within that time, 24 castings were scrapped due to dirt and 26 were scrapped due to occurrences of misrun, resulting in a filling-related scrap rate of approximately 3%.

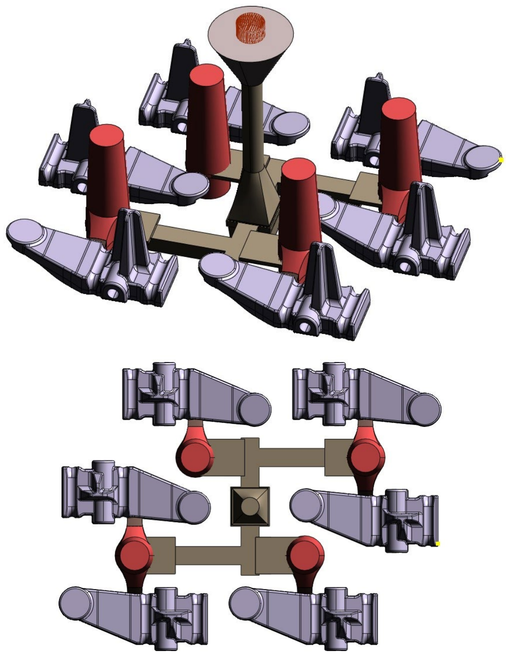


Figure 6. Pattern design shows the starting configuration of the runner system.

To perform the Generative Gating Methodology, in Phase One a steady-state simulation was first set up. The sprue dimensions, riser dimensions, and filter print were kept constant from the original gating. The build volume for the runner was defined a 0.5” thick and was drawn such that it avoided the complex parting line and did not come with 0.5” of the casting, shown in Figure 7. An inflow was placed at the base of the sprue and outflows were placed on the back of each casting. The flow rate was set to match the rate that operators typically pour this casting. One additional note is that the original system was choked through a combination of resistance from the filter and where the runner meets the filter print. When the input volume for the steady-state simulation was designed, these chokes were kept constant. This prevented one system from performing better than the other in future trials, due to filling the straight sprue faster.

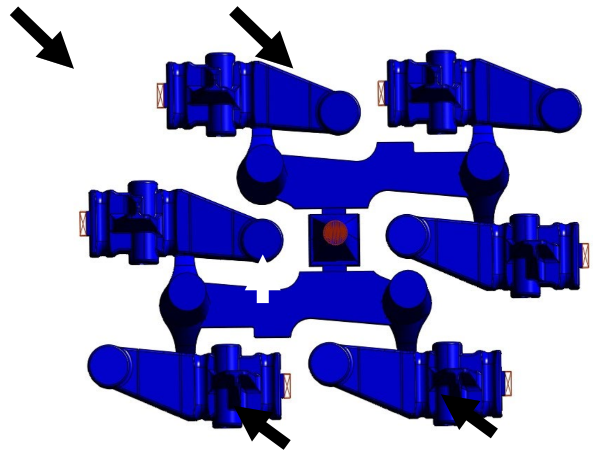


Figure 7. The geometry input for the steady-state simulation is shown. The runner shape was designed to avoid complex parting-line features. The red cylinder located at the base of the sprue is the inflow (indicated with a white arrow), and then red wire-frame blocks at the backs of each casting are the outflows (select outflows are indicated with black arrows).

The Phase One simulation was run, and the velocity results were used to produce a runner model, shown in Figure 8. The maximum velocity is 9.7 in/s. The critical velocity was chosen as 3 in/s, to remove some runner material but not break the connection between the casting and the sprue. The part of the runner that was below 3 in/s was filtered out. The phase one model was exported as an STL file and made into a watertight model using a specialized STL editing software, completing phase one of the method.

To begin Phase Two, the runner model was imported into a copy of the baseline simulation, and the original gating was removed. The simulation was then run, and the velocities examined (Figure 9). The maximum velocity in the runner was approximately 65 in/s at steady state. The critical velocity of 15 in/s was chosen, and velocities slower than 15 in/s were filtered out. The phase two model was exported as an STL and again made into a watertight model using STL editing software.
The Phase Two model was imported back into the simulation software and simulated to verify the quality of the runner system. Once the runner system was shown to match the quality of the existing runner system, the STL model was traced to build a STEP (STandard for the Exchange of Product model data) surface model. The STEP surface model was modified to obtain a drafted model that met the draft requirements of the foundry’s manufacturing process, with every effort made to

maintain the shape and local cross-sectional areas. The final STEP surface model (Figure 10) was simulated to verify that it performed similarly to the generated model.

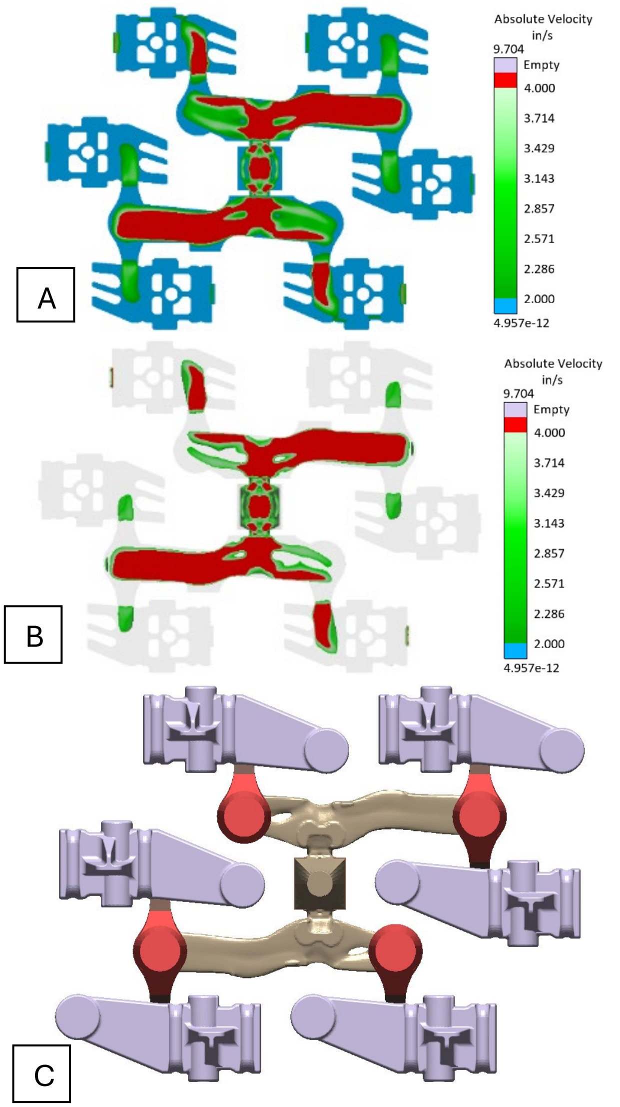


Figure 8. A) The velocity generated by the steady-state simulation is shown, with a scale showing velocities regions 2 in/s in blue, regions above 4 in/s in red, and regions in between in green. B) The result is filtered to only show regions above 3 in/s. C) The exported geometry is shown after it was imported into the phase two simulation.

The final STEP model retained the rough surface of the runners and the hole near the closer riser, to better understand their impacts. Each of these are quite uncommon features that few engineers would intentionally include in a runner design.

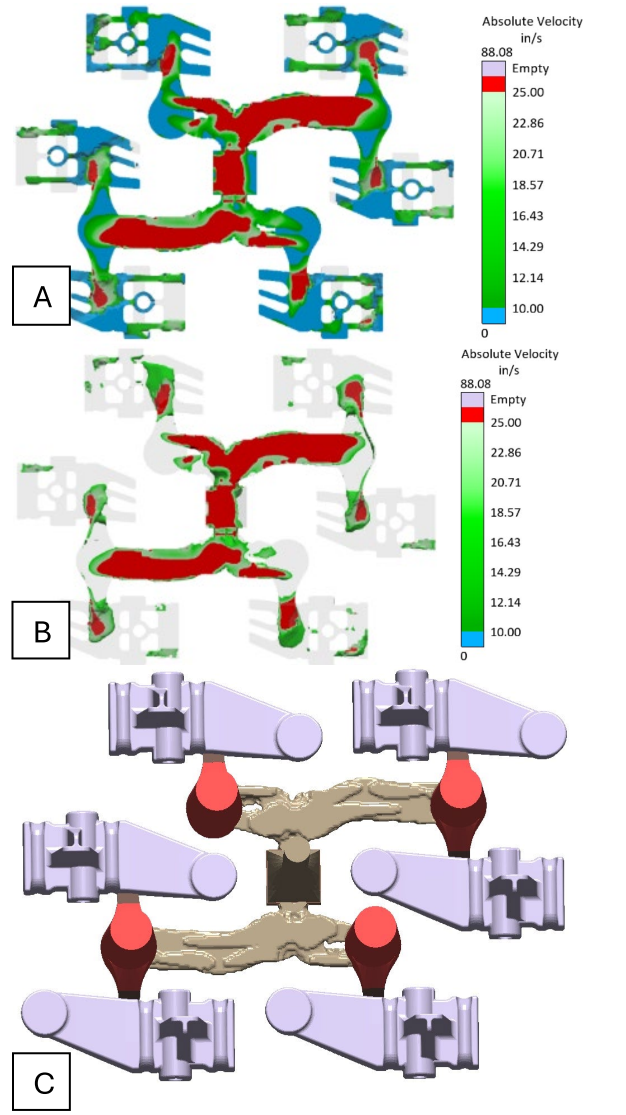


Figure 9. A) The velocity generated by the steady-state simulation is shown, with a scale showing velocities regions 10 in/s in blue, regions above 25 in/s in red, and regions in between in green. B) The result is filtered to only show regions above 15 in/s. C) The exported geometry is shown after it was imported into the phase two simulation.

The generated runner design reduced the cast weight of the runners between the filter and the risers from approximately 16.8 lbs. to approximately 9.2 lbs., a weight savings of 46%.

The FDM (fused deposition modeling) 3D printed runners were produced to replace the runners on the existing tooling (Figure 10). A removable piece allowed for two different versions of the pattern to be poured (Figures 11 and 12). Five molds were planned to be poured with 0.5" of well under the filter and five molds were to be poured with 1.0" of well under the filter. The decision to test an extended well was made due to the relatively small connection between the generated runner and the filter, which potentially risked clogging with slag or other filtered inclusions.

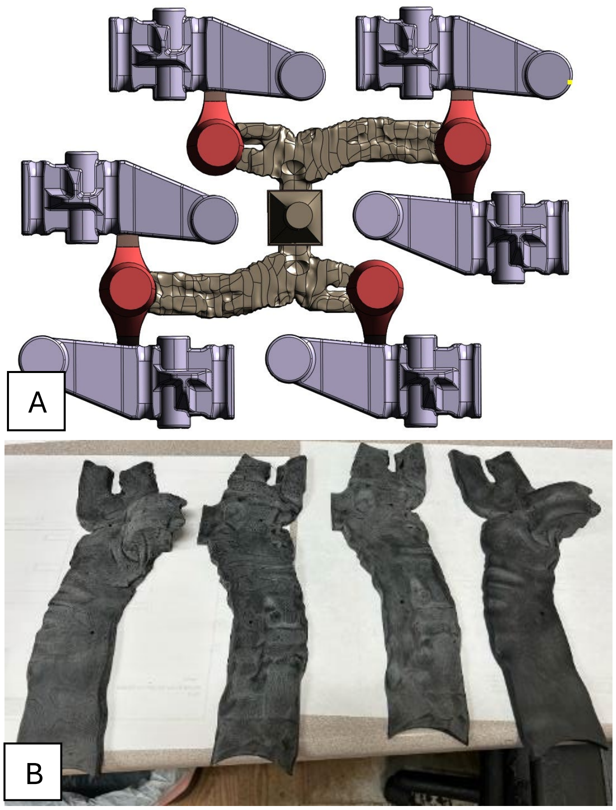


Figure 10. A) The STEP surface model is shown. B) The resulting FDM 3D printed runners are shown, following sanding.

The castings were molded and poured. Eight molds were poured with the 0.5" well, with ladle temperatures beginning at 2535F (1391C) and ending at 2466F (1352C). Six molds were poured with the 1.0" well, with ladle temperatures beginning at 2523F (1384C) and ending at 2400F (1316C).

Fourteen total molds were produced, for a total of 84 castings. Each mold was numbered, and the castings were kept with their sprues.

No significant challenges were encountered during molding or pouring.

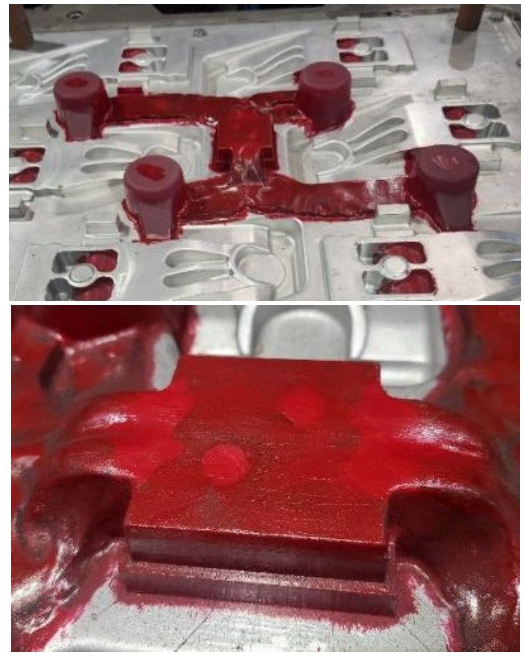


Figure 11. Shows the 3D printed pattern pieces with the 1.0" well, inserted onto the machined plate.

Figure 12. The 3D printed pattern pieces with the 0.5" well inserted onto the machined plate are shown.

RESULTS

SIMULATION RESULTS – FILLING QUALITY

Simulation results for the final generated runner were reviewed in detail and compared to simulation results for the original runner.

For the generated gating system, “success” was defined as matching or improving upon results of the baseline runner system. The simulation results selected for evaluation are metal temperature, air entrapment, cumulative metal front surface area, and maximum velocity against the mold wall.

The first result examined was the metal temperature. One of the primary goals in metalcasting is to deliver metal to the entire casting before it gets too cold to flow. The temperature of the melt front is very dependent on chokes in the runner system (when pouring rate and metal temperature are held constant); which were held constant to make the baseline and generated runners comparable. In the baseline runner system, the coolest metal occurred when the front entered the tip of the casting, where it had cooled to 2242F (1228C), approximately 2°F (1.11°C) above the nominal liquidus. In the same location, the generated gating had only cooled to 2262F (1239C), which is 22°F (12.2°C) above liquidus. The higher filling temperature may remove any risk of cold metal defects due to process variation. The generated gating met or exceeded the filling temperature of the baseline at all locations.

Air entrapment is important to consider when determining the “quality” of a gating system, as air and metal mixing can cause oxidation inclusions and dissolved gas defects. When comparing air entrapment, there are two primary sources of air and metal mixing to consider. The first is in the sprue. Before the sprue is full, constant air entrapment occurs due to entrained air bubbles. With a straight sprue, back pressure from the filter and runner system are required to fill the sprue. Thus, the gating system that provides more back pressure will fill the sprue faster and have less overall air entrapment. A tapered sprue would eliminate this issue, however the molding machine utilized can only accept straight sprues. The cross section where the filter print meets the runners was kept the same in the generated gating to keep the two systems roughly comparable.

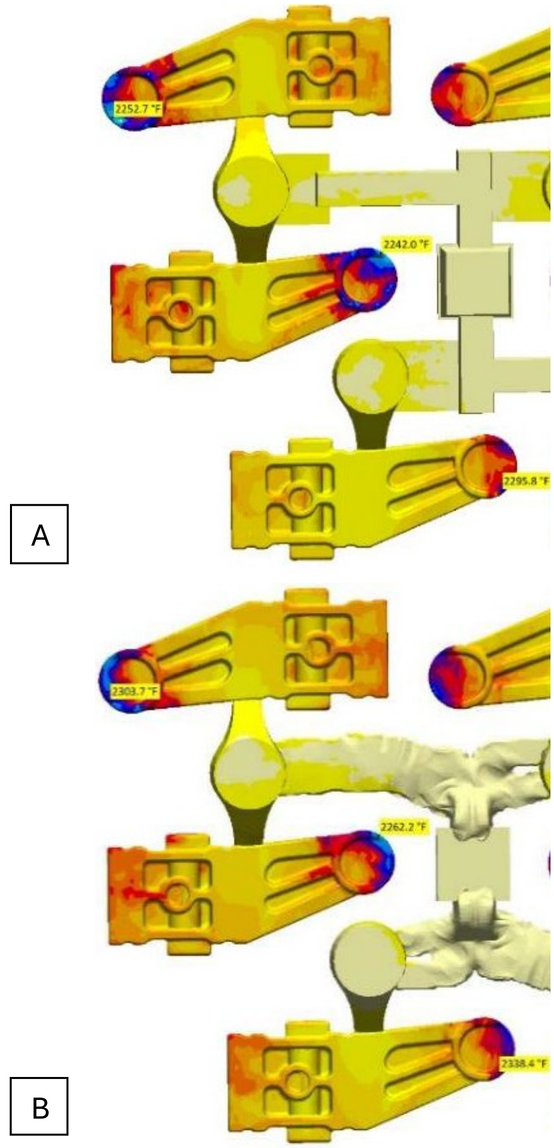


Figure 13. The filling temperature result is shown, which indicates the temperature of the melt front as it crossed each location. A) The original runners are shown, with temperatures dropping to 2242F (1228C). B) The generated runners are shown, with temperatures dropping to 2262F (1239C).

In the 8 second total pouring time, the baseline system filled the sprue completely in 7.1 seconds, and the generated gating filled the sprue at 7.5 seconds. The average air entrapment values in the sprue, accumulated over the duration of pouring, were 2.9% by volume for the baseline runner, and 4.0% by volume for the generated runner. The results suggest that the generated runner put less back pressure on the sprue, increasing its total average air entrapment.

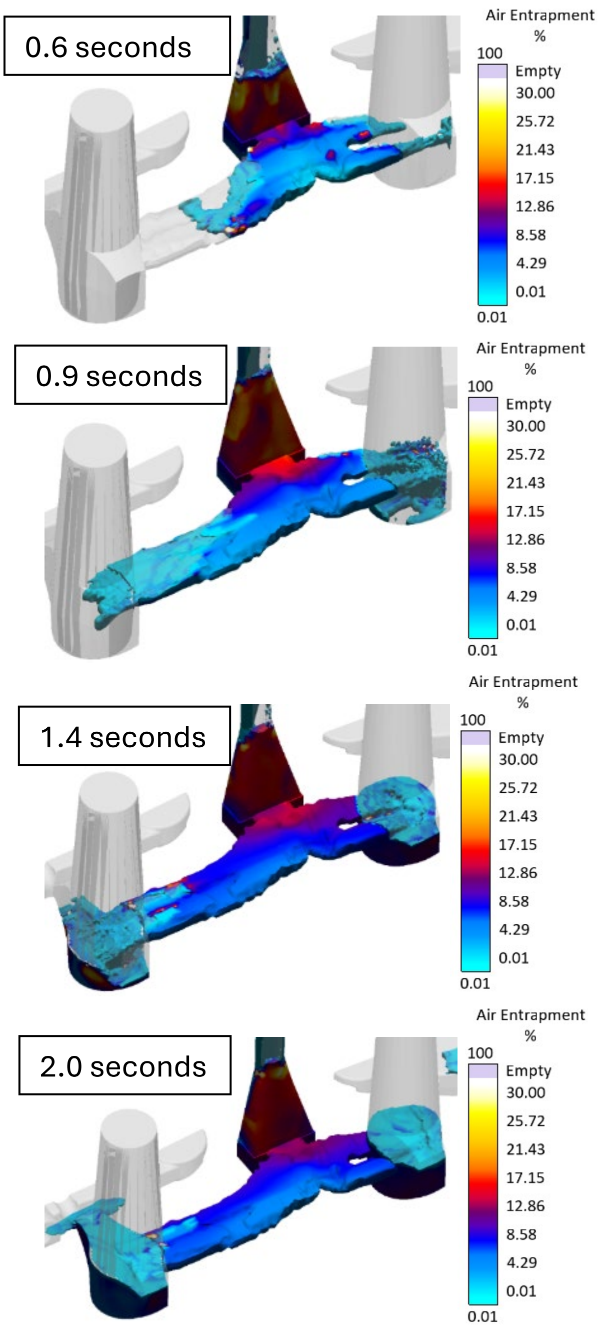


Figure 14. The air entrapment result is shown for the generated gating. The air entrapment is shown at different times, displaying the filling pattern.

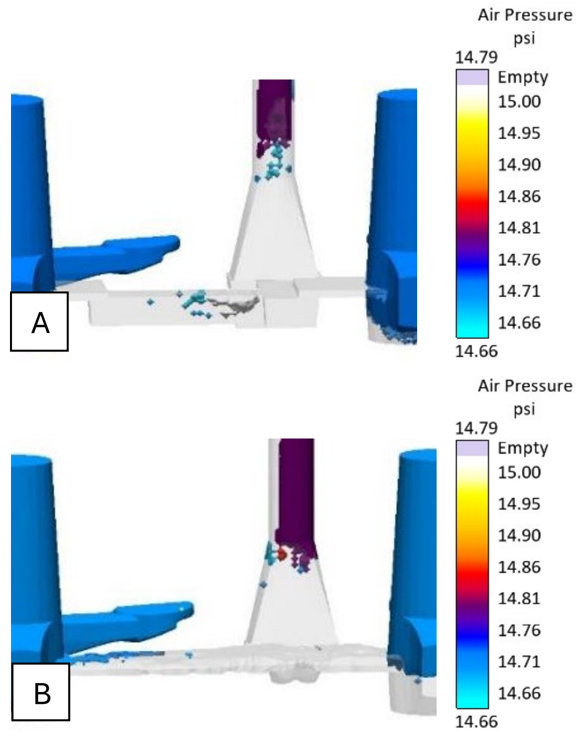


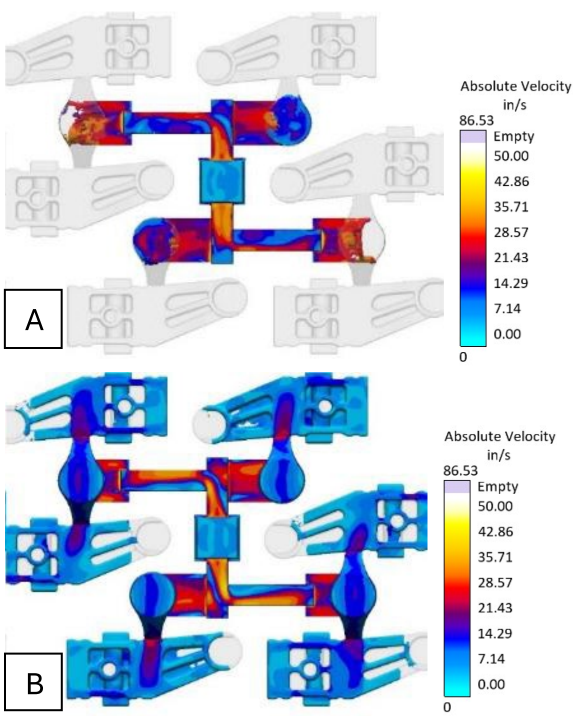
Figure 15. Shows the air pressure result, which identifies air pocket that are present in the runners, captured 1.3 seconds after pouring began. A) The original runners are shown with an air pocket in the center of the runner. B) The generated runners are shown with air pockets in the top of the runner near where it meets the riser.

The second source of air entrapment is air pockets that collapse when the runner, risers, and castings are filled. This source is highly dependent on the runner system design, including local cross-sectional areas. Low air entrapment values require a runner that minimizes splashing and avoids sustained air pockets. At the end of pouring, the castings in the baseline system had an average air entrapment of 2.9% by volume, and the generated gating delivered an average air entrapment of 3.4% by volume (17% more than the baseline). These values include air trapped while filling the sprue, runners, risers, and casting itself.

Air pockets sustained in the runner were further examined. Sustained air pockets give rise to a continuous stream of air entrapment as metal flows past them. Air pockets in the center of the baseline runner were sustained until 1.8 seconds into pouring (Figure 15). Air pockets in the generated runner were present on the top surface of the runner near the riser only, where metal waterfalls into the base of the riser.

The total surface area of the metal during filling is also an important consideration. As molten metal splashes, the surface area of the metal increases and exposes the metal to oxygen. Reactions between the metal and oxygen can cause oxidation inclusions. The baseline gating system produced a cumulative surface area of approximately 0.142 square meters. The generative runner system produced a cumulative surface area was approximately 0.136 square meters (4% less than the baseline).

The final result evaluated was the velocity in the runner systems. Velocities were compared during initial filling (at 1 second, before steady state is reached) and as soon as steady state was reached (at 4 seconds). The primary concern is that the foundry commonly encounters mold erosion where simulated velocities surpass 50 in/s. Nowhere on either the baseline or the generated gating does the surface velocity surpass 50 in/s during initial filling nor at steady state.



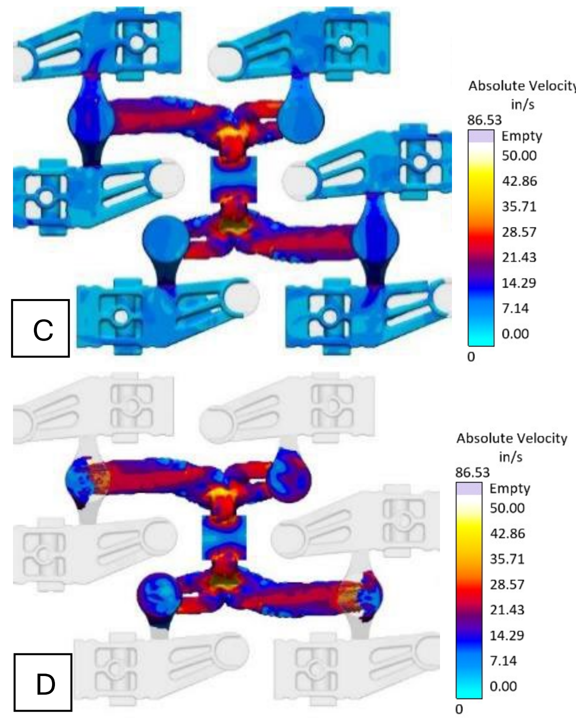


Figure 16. Shows the velocity of the metal, in the original runners, captured 1 second after pouring began (A) and 4 seconds after pouring began (B). The velocity of the metal in the generated runners at 1 second (C) and 4 seconds (D).

Velocity profiles while the runners filled were examined in detail. Like most runner systems, the velocity of the metal forces the inital melt front up against the back wall, as it rounds the corner of "T" intersection (Figure 17, 0.6 sec.). However, by the time the melt front reaches the end of the runner (0.9 sec.), the flow pattern began to evenly waterfall into the runner. After the metal reaches the gate into the riser, the runner mostly fills except for the last few inches before the riser, similar to the condition shown in Figure 18. The runner does not fill completely as there is no choke at the riser gate to apply back pressure.

Velocities near the "hole" in the runner were far below 50 in/s and did not appear to be at risk of eroding the mold. Similarly, the jagged top features showed low velocites and were determined to not have a major risk of mold erosion.

By comparing the metal temperature, air entrapment, cumulative metal front surface area, and maximum velocity against the mold wall, it was concluded that the generated runner system performed equally well in simulation when compared to the baseline design.

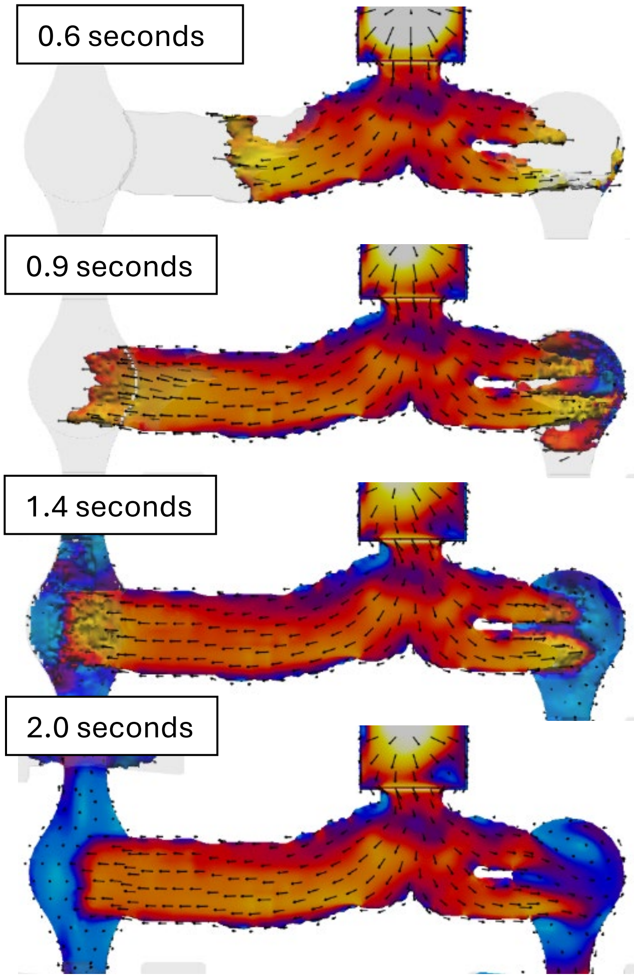


Figure 17. The velocity of metal over time as it first fills the generated runner. The result is sectioned to show the center of the runner.

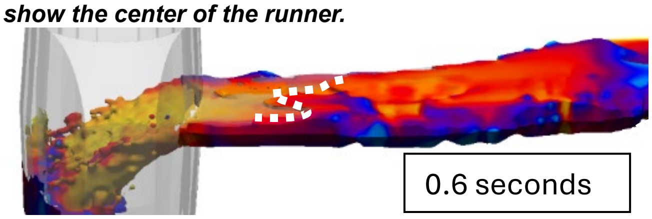


Figure 18. The velocity of the metal in the generated runner, shown at 0.9 seconds. The melt front is highlighted with a dotted white line.

PHYSICAL TRIAL RESULTS

There were 8 molds with the 1.0" well and 6 molds with the 0.5" well were produced, for a total of 84 castings. There were 77 castings retained for inspection. Two complete sets of sprues, castings, and runners were retained for inspection. One set was shot-blasted, and the other set was left in the as-cast state. The two main areas of investigation were the quality of the castings and examination of the runners, with a focus on evidence of mold erosion, evidence of slag or reoxidation inclusions, and presence of gas bubbles.

CASTING QUALITY

The quality of the castings made with the generated gating were compared to scrap data from production of castings with the original gating. Recall that of the last 1700 castings produced with the original pattern, 24 castings were rejected due to "dirt" (1.4%) and 26 castings were rejected due to misrun (1.5%).

Of the 77 retained sample castings produced with the generated gating, one casting was rejected due to a negative indication. The rejected casting was produced with the 0.5" well following the filter. The casting was rejected due to a deep negative that could not be properly identified without sectioning. The defect is shown in Figure 20.

With one casting of 77 rejected due to a defect that may potentially be labeled as "dirt," the resulting rejection rate would be 1.3%, which is in line with historical scrap for the original gating. Although this sample is too small to be statistically significant, it confirms that the approach is reasonable and does not frequently cause major defects.

Figure 19. The 77 castings reserved for analysis, with the two intact sets left out.

FILLING QUALITY

One set including a sprue, runner, risers, and castings was retained and shot-blasted for further inspection, which was produced with the 1.0” filter print. The runners were inspected for evidence of mold erosion, evidence of slag or reoxidation inclusions, and presence of gas bubbles. No evidence of mold erosion was encountered in the sprue, runners, risers, or castings, shown in Figure 21. A special focus was paid to where the well meets the runners in the drag, as that showed the highest sustained velocities in the simulation results. However, no positive metal or mold erosion were found in that location. Special attention was also paid to the “hole” in the runner near the riser closest to the sprue, however no positive metal or mold erosion were identified in that location either (Figures 21 and 22).

Figure 20. The casting produced with generative gating that was rejected due to a negative indication. Left: The complete casting. Right: A close-up of the defect.

Negatives were present on the cope surface of the runner. The negatives appear to be the result of slag inclusions based on their morphology, along with other observations: first, negatives are present above the filter (Figure 22), suggesting that the metal entering the sprue contains slag, and that the filter is trapping a portion of it. Velocities through the filter are up to 18 in/s at steady state, which may be capable of pulling slag particles through the holes in the extruded filter. Second, the negatives on the runners are settled in locations with lower surface velocities. These are locations where slag could settle without being washed deeper into the system.

The other possible origin of the slag is that it formed due to air bubbles trapped against the cope side of the runner. A method of smoothing the rough surface may avoid this condition in the future.

The risers immediately follow the runners and likely caught any slag that passed the runners. This makes it impossible to determine the impact slag would have had on the castings.

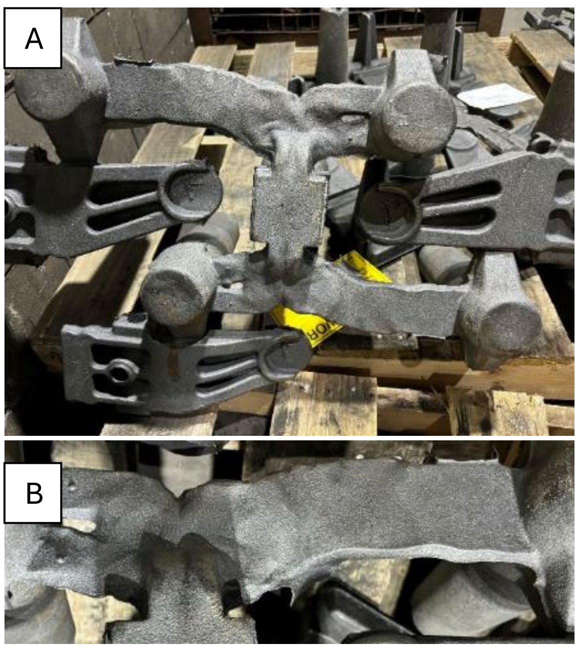


Figure 21. The drag side of the generated runners poured in the physical trials. No evidence of mold erosion was identified anywhere on the runner system. A) Full view of the entire rigging system. B) Close-up of one runner.

DISCUSSION

DISCUSSION OF RESULTS

The simulated and physical trials both demonstrate that the Generative Gating Methodology is capable of producing runners that yield high quality castings. The simulated results showed that the generated runners offered higher filling temperatures at the cost of not backing up the sprue as quickly. Tapered sprues may resolve this issue. The physical trials yielded one scrapped casting out of 77, closely matching the established scrap history with the original gating. However, further trials would be required to obtain a significant statistical sample.

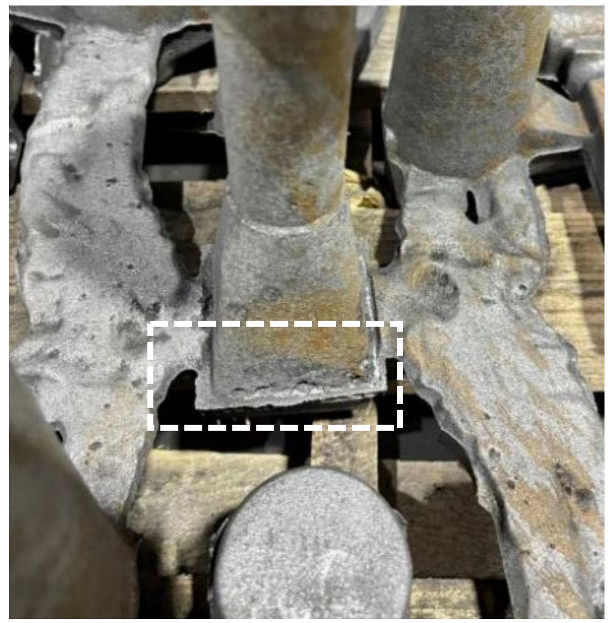


Figure 22. The cope side of the generated runners poured in the physical trials. The area above the filter is highlighted, showing slag inclusion indications.

Figure 23. The cope side of the generated runners poured in the physical trials. Slag inclusion indications are present in the top of the runner.

The success of these trials paves the way for further research into optimal parameters and applications for the Generative Gating Methodology.

DISCUSSION OF MANUAL INPUTS

The Generative Gating Methodology requires a number of manual inputs to provide successful results. Variations on these inputs have a substantial impact on the generated gating system. The impact of each variable was beyond the scope of this case study, but some insights were still gained.

Sprue size and gate dimensions determine the **gating ratio** of the initial steady-state simulation. For the case study, the starting cross-sectional areas were approximately 1.8 in^2 at the sprue, 3.4 in^2 between the filter print and runner, and 5.2 in^2 where the runner met the risers, to match the baseline system. This yields roughly a 1:2:3 gating ratio. The final cross-sectional areas of the generated gating system were 1.8 in^2 at the sprue, 2.2 in^2 between the filter print and runner, and 4.6 in^2 where the runner met the risers. The generated runner reduced the gating ratio to roughly 1:1.5: 2.5.

The selected thickness of **the allowable build volume** has a substantial impact on the final runners. The case study was run with a 0.5" tall build volume, however some initial trials were run with a 1" tall build volume. As a result, the initial trials had significantly more vertical leeway and developed helix-like spiraling runners with hollow centers. By reducing the height of the build volume, the runners were much less likely to develop hollow sections.

In the case study, **critical velocities** were selected manually after each version had run. A lower critical velocity value will filter out less of the runner volume, leading to larger runners and potentially air pockets. A higher critical velocity filters out more of the runner volume, making the metal flow faster in some cases but cutting off flow entirely in others. The values used in the case study were chosen to be relatively close to where the flow gets cut off, although the actual value was arbitrary and based on the author's prior experience with what appeared to produce a "reasonable" runner.

Additional iterations were evaluated during the case study but not used to produce the final version. It was found that additional iterations increased the velocity of the metal (due to the shrinking runner) and lead to worse air entrapment and surface velocity results. Intentionally expanding the runner between iterations may make this more feasible.

FUTURE WORK

Further investigation into Generative Gating is required to make the process fast and consistent. Recommendations need to be developed for:

- Starting build volume – gating ratio, thickness, how to include traps/runner extensions and other features
- Critical velocities – study impact of a variety of velocities with different casting weights and choke areas
- Additional iterations
- Geometry smoothing
- Automating the procedure
- Results to consider in addition to velocity

DISCUSSION OF LIMITATIONS

One of the largest challenges for the Generative Gating Methodology is turning the resulting gating models into drafted pattern models. In this case study, significant effort was put into surface modeling to trace the generated runner such that draft could be applied. Efforts to roughly trace the model with trapezoids of matching cross sections failed to produce a runner design that minimized air entrapment as well as the unmodified generated runner. This limitation may be possible to overcome for traditionally parted molds. One option would be to further thin the build volume, such that the runner cannot deviate significantly from the parting line. Another option may be 3D printing runner patterns with complex parting lines that follow the centerline of the generated runner. One further option would be to produce cores to form the runners, however this would add cost.

This limitation is quickly resolved when sand molds are 3D printed, and the resulting generated gating geometry can be printed without adding draft. Similarly, 3D printed sand cores containing the runner may be inserted into traditionally parted sand molds.

CONCLUSION

In conclusion, this case study shows the viability of the Generative Gating Methodology for producing runners of similar quality to those produced manually by experienced foundry engineers.

The Generative Gating Methodology of extracting velocities above a critical value from metalcasting flow simulations, creating 3D runner geometries. The method begins by defining a volume where runners are allowed to be built, in a simulation setup that includes the sprue, gates, and castings. The simulation is run at steady state, and high-flow volumes are exported. Those volumes are imported into a standard (non-steady state) simulation and run again with filters, chills, and other features. The high-flow areas are extracted from the results and simulated again to verify the quality of the resulting runner system. When the Generative Gating Method was applied to a production casting, the case study found that:

- The Generated Gating provided a reduction in runner weight from approximately 16.8 lbs. to approximately 9.2 lbs., a weight savings of 46%.
- Using Generated Gating, temperatures during filling met or exceeded the temperatures achieved with the original system.
- Using Generated Gating, the average cumulative air entrapment during filling was 3.4%, compared to 2.9% in the original system. Cumulative surface area, however, dropped to 0.136 square meters compared to 0.142 square meters in the original system.
- Neither the Generated gating nor the original system exceeded 50 in/s, reducing the risk of mold erosion.
- Of the 77 castings reviewed from the Generated Gating sample, only one casting was rejectable, producing a scrap rate of 1.3%. The rate is comparable to the scrap rate due to "dirt" in historical data of castings produced with the original gating.

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