Development of Universal Gating System Tool for the Sand-Casting Industry

Jake Officer, Ismail Fidan, and Fred Vondra

Department of Manufacturing and Engineering Technology
College of Engineering
Tennessee Technological University
Cookeville, TN 38505-5003
USA

Abstract

Proper gating systems can be the determining factor of whether a casting has excellent quality, or has defects present. This is why optimizing gate systems plays an important role in improving the quality of castings. Due to the lack of precision in gate creation methods, inconsistencies exist across different casting processes. This research aims to address this by developing a framework for the creation of a universal gating system. This study seeks to develop a universal gating tool to ensure consistent and efficient castings by analyzing various gate systems using Inspire Cast and examining casting yields with various gating systems. The goals of this work-in-progress study include achieving optimal metal flow, minimizing defects, and enhancing yield. This universal gating tool (UGT) offers a standard approach to gate design, which leads to improved quality and efficiency, reductions in production costs, and enhancements in the quality of cast components.

Introduction

Metal casting is a form of manufacturing that dates to the bronze age. Because of its relatively easy-to-develop tools and abundant rare material in the form of metal ore, metal casting quickly developed across many areas of the world with evidence of metal casting technology existing in ancient Greece, India, and China. Metal casting involves a process of creating a mold and then filling that mold with molten metal to create a casting [1]. Sand casting is the most common form of metal casting used in industry today due to the relatively low cost of the sand used in sand casting operations.

A mold consists of a few major components. These are the pattern cavity, runner bar, ingates, risers, sprue, and pouring basin. Each of these components is critical for the success of a casting and the improper design of any component can lead to drastic errors in the final product. Among these components, the ingate remains a critical part of the gate system as it controls the flow of metal into the mold cavity determining the flow rate and filling rate as well as contributing to the overall surface quality and integrity of the casting [2] [3].

There have been many attempts to optimize the design of ingates to address one specific aspect of a gate system. Because of these attempts to research the optimization of gate systems, there have been many improvements in the field of gate system design.

All these previous works have been a great benefit to the metal casting industry. Despite the advancements made regarding the design of the gates pre-mold, the system for creating a gate has not made a substantial change in many years.

The process for creating a gate system involves using a trowel or double-ended tool to carve away sand from the cope and drag of the mold to create the gates and runner bar respectively. This process leads to inconsistent geometry and the need for extra machining as the gate system has to be cut off and the surface of the part refinished. Because of this imprecise method, there also exists an issue of defects that occur in the castings such as erosion, cold shuts, or shrinkage due to the gate system not accurately matching the design created using simulation or CAD tools.

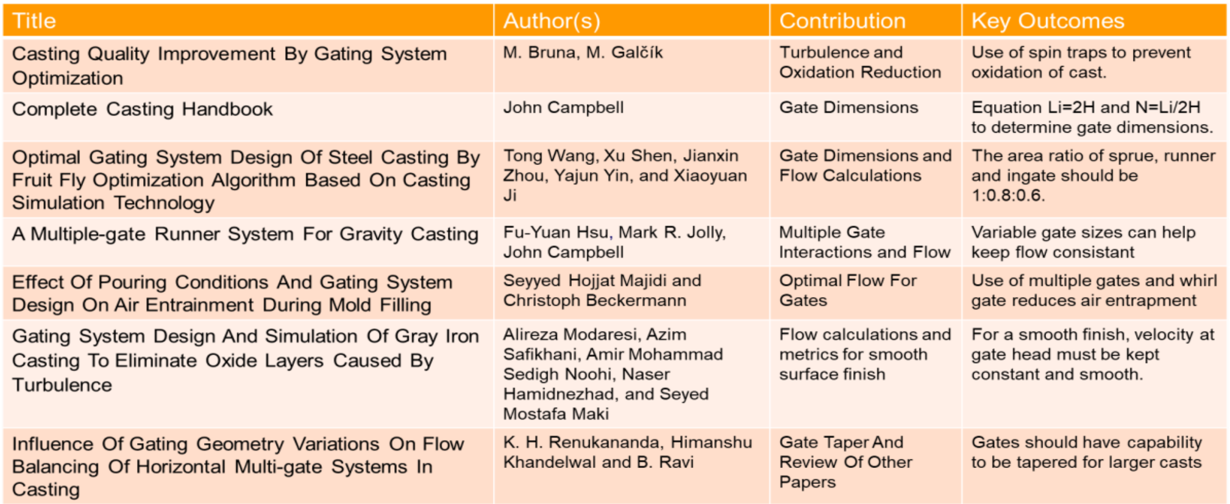
The development of simulation programs like InspireCast has greatly improved the gate design process by allowing for systems to be tested without the need to make the mold and pour to see how the mold will fill. However, due to the issue addressed before that the gates are typically hand carved, the real results may not match what was initially simulated. Because of this, it is desirable to design a better system for gating that allows for gate systems to be consistent with CAD and simulation designs.

The work presented here seeks to understand the previous work done in the field of gate system optimization to create a new set of gate-creation tools. This set of tools will apply the standard mold creation principles while also applying the concepts optimized in previous research to create a universal tool able to create consistent gates that will have properties matching expected results in simulations as well as allow for the reduction of defects in castings constantly.

Literature Review

To assist with this project, it is important to understand the current standings of gate design in metal casting. While universal standards do not currently exist for all systems, great developments have been made regarding the parameters of the gates [4]. A summary of these previous findings can be found in Table 1 [2][3][5][6][7][8][9], a few crucial conclusions can be drawn.

Table 1. Existing literature and their outcomes



Title	Author(s)	Contribution	Key Outcomes
Casting Quality Improvement By Gating System Optimization	M. Bruna, M. Galčík	Turbulence and Oxidation Reduction	Use of spin traps to prevent oxidation of cast.
Complete Casting Handbook	John Campbell	Gate Dimensions	Equation Li=2H and N=Li/2H to determine gate dimensions.
Optimal Gating System Design Of Steel Casting By Fruit Fly Optimization Algorithm Based On Casting Simulation Technology	Tong Wang, Xu Shen, Jianxin Zhou, Yajun Yin, and Xiaoyuan Ji	Gate Dimensions and Flow Calculations	The area ratio of sprue, runner and ingate should be 1:0.8:0.6.
A Multiple-gate Runner System For Gravity Casting	Fu-Yuan Hsu, Mark R. Jolly, John Campbell	Multiple Gate Interactions and Flow	Variable gate sizes can help keep flow consistant
Effect Of Pouring Conditions And Gating System Design On Air Entrainment During Mold Filling	Seyyed Hojjat Majidi and Christoph Beckermann	Optimal Flow For Gates	Use of multiple gates and whirl gate reduces air entrapment
Gating System Design And Simulation Of Gray Iron Casting To Eliminate Oxide Layers Caused By Turbulence	Alireza Modaresi, Azim Safikhani, Amir Mohammad Sedigh Noohi, Naser Hamidnezhad, and Seyed Mostafa Maki	Flow calculations and metrics for smooth surface finish	For a smooth finish, velocity at gate head must be kept constant and smooth.
Influence Of Gating Geometry Variations On Flow Balancing Of Horizontal Multi-gate Systems In Casting	K. H. Renukananda, Himanshu Khandelwal and B. Ravi	Gate Taper And Review Of Other Papers	Gates should have capability to be tapered for larger casts

Although the use of the additive manufacturing is greatly growing in several aspects of the casting field, this article does not specifically report the use of the technology in gating design. However, it is evident that additive manufacturing is one of the most commonly used fabrication technologies used for making gating systems.

Gate Shape

The shape of a gate can be critical to the success of any metal casting project. This is because the shape of the gate has a direct influence on the flow rate and turbulence of the liquid metal as it flows into the mold. Because of this, it is critical to understand the principles that apply to flow and turbulence to determine the shape needed for the UGT. The gates must properly reduce the velocity of the liquid metal so that it enters the mold cavity at between 0.5-1.0ms^-1 [3]. If there is an improper gate shape and the velocity of the liquid metal were to increase to over 1.0m/s ^-1 the final part will have issues regarding surface qualities and holes caused by sand erosion.

The gate shape must be wide enough for the liquid metal to pass through effectively without jetting, but also small enough to make sure the mold cavity fills fully and without cold shuts. There are a few methods that need to be considered to determine the right area for these gates.

The first method typically used to determine gate area is to use ratios between the size of the sprue, runner bar, and gates. Because the liquid metal is at its highest velocity when exiting the sprue, the goal of the runner bar and gates is to reduce this velocity to the optimal range previously established [3]. One common ratio used is 1:2:4 which means that the area of the sprue exit is X, the area of the runner bar is 2X, and the total gate area is 4X. While this method can be successful, studies have found that at sprue heights over 200mm, the ratio becomes ineffective at accurately reducing velocity [3].

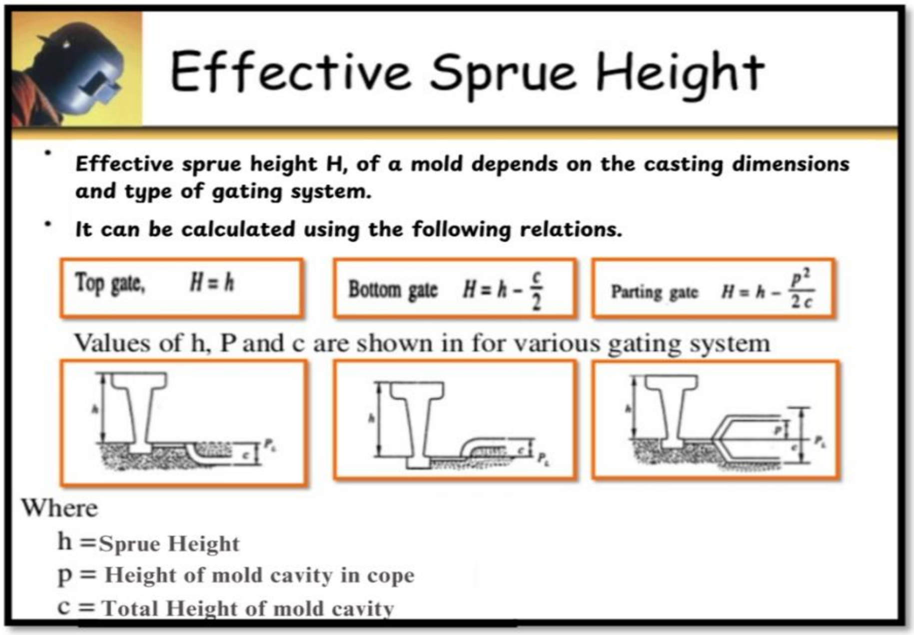
The second method of determining gate area is to use a function of the sessile drop to predict how to reduce velocity. From this method, a base of 1000mm^2 is allotted for the total gate area. Next, a calculation to find the length of each gate and the number of gates needed to determine the final geometry of the gates. By determining the sessile drop of the metal, the length of the gate can be determined using the equation Li = 2H where Li is the length of the gate and 2H is twice the height of the sessile drop [3]. In Aluminum which will be cast in this paper, the sessile drop is 13mm which means the gates must be less than 26mm long. Next, the equation Li/N=2H can be used to determine the length of the gates based on the needed number of gates, or the equation N=Li/2H to determine the number of gates based on the needed length of the gates [3]. Utilizing both equations will allow us to calculate the optimal lengths for our gate segments in the UGT.

Knowing the total gate area needed of 1000mm^2 for the Aluminum casting, we can then use the previous equations to determine our gate geometry. There will be 5 coupons casted using the UGT so inputting 5 for N gives the gate length of 130mm for each gate. By using the equation TGA/N =SGA where TGA is the determined total gating area and SGA is the gating area of a single gate, it can be determined that 200mm is the area needed for each gate. From this, the final gate dimensions of 1.5mm x 130mm can be determined for the UGT Aluminum casting. These same equations can be used to create sections for any metal or cast as long as the sessile drop and number of gates can be established.

Empirical Knowledge Elements for Gate design

Scientific discoveries and subject matter experts have developed several knowledge blocks to present the links and interactions of the gating system design components. They mostly report the quality of castings, types of risers, methods for sprue/riser design including the Chvorinov rule and modulus method, design rules, and their linkages to other parameters related to materials and processes. In some cases, even the best practices are captured.

Dimensions using these methods based on properties of the casting such as volume, surface area, and solidification time are formulated and presented as empirical knowledge elements. Figure 1 shows an example that is related to sprue height [10].



Effective Sprue Height

- Effective sprue height H, of a mold depends on the casting dimensions and type of gating system.
- It can be calculated using the following relations.

Top gate, $H = h$

Bottom gate $H = h - \frac{c}{2}$

Parting gate $H = h - \frac{p^2}{2c}$

Values of h, P and c are shown in for various gating system

Where

h =Sprue Height
p = Height of mold cavity in cope
c = Total Height of mold cavity

Figure 1: Example of an empirical knowledge element related to sprue height

Feature Based Rules

In any part design, there is a high number of individual features called boss, hole, web, draft, and chamfer. The design of these features on any gating system is different for all materials and casting processes. So, the handbooks and catalogs of the casting practices contain the numerical data blocks of these features [11]. Figure 2 shows a sample of features available on a gating system.

Design of Universal Gate Tool

Based on the collected data the final design and features of the UGT were finalized. The first thing that must be integrated is the modularity of the tool. Because each casting may require gates of different lengths or widths, the UGT should be adjustable to allow for different thicknesses or shapes of gates to be added to the same runner bar. This is accomplished by designing the UGT to have modular runner bars and gates as shown in Figure 3 [12].

The use of magnets embedded in the top of the runner bar and the bottom of the gates allows for gates of any size or shape to be placed along any section of the runner bar. The linking magnets located at the front and back of the runner bar and gate segments allow for the gates and runner bars to be customized to any size [12].

Future work with the design of the UGT components involves adding more possible features like whirl gate segments or slag traps to allow for a broader range of casting applications.

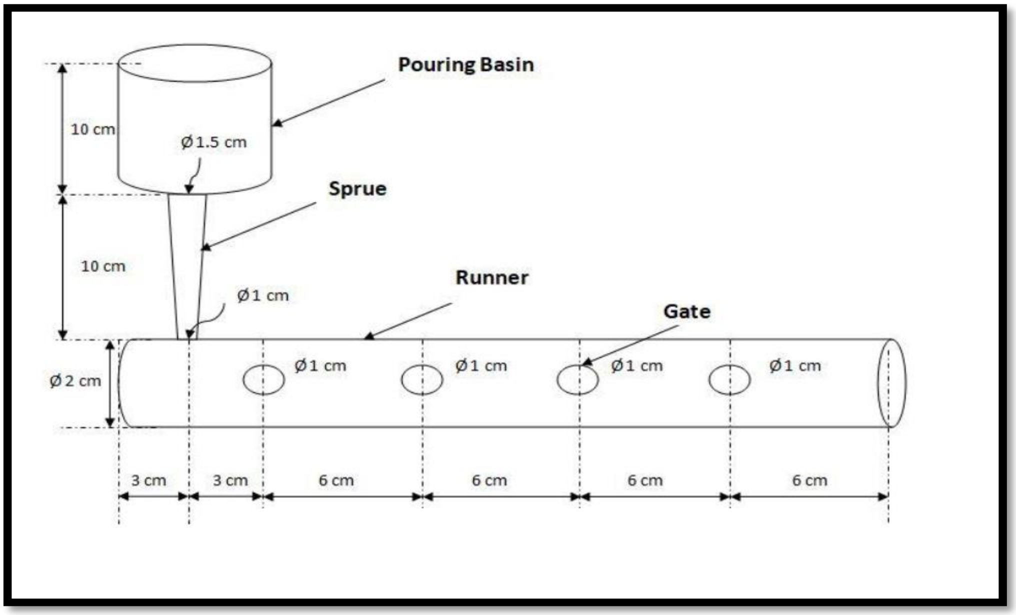


Figure 2: Feature-based knowledge elements on a sample gating system

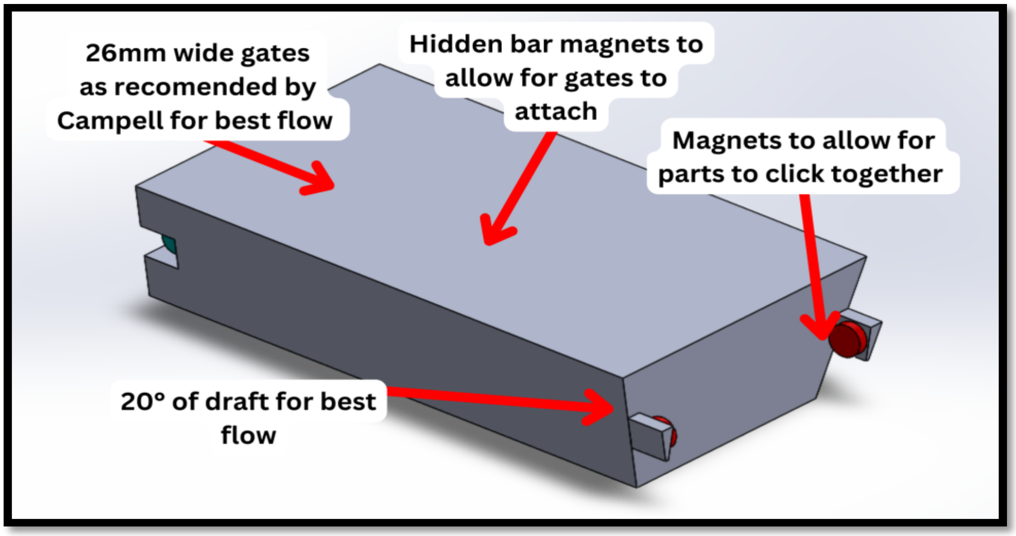


Figure 3. Modular section of runner bar and its features

Physical Testing

For the later physical testing of the UGT, a design was created using the UGT to cast five tensile testers. These serve a two-fold purpose. First, the flat profile of the testers as shown in Figure 4 allows for quick visual inspection of the part to look for shrinkage or holes in the casting. Secondly, the testers can be taken to a testing facility to analyze the microstructure and mechanical properties of the casting. By comparing the tensile testers made using the traditional method of gate creation compared to the UGT, a conclusion can be drawn about the effectiveness of the UGT. However, before physical testing can be done the casting must be simulated.

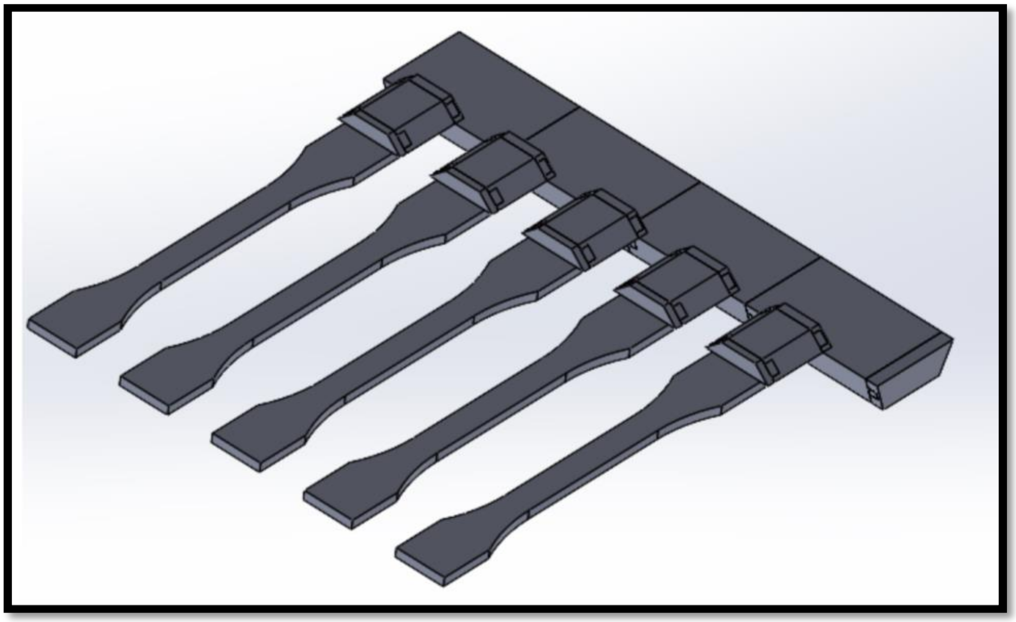


Figure 4. Design of UGT for tensile testers

Simulation-Based Knowledge

Today, there is a high number of casting simulation tools helping practitioners solve their problems without engaging themselves in real casting practices. Such kinds of tools help the practitioners to solve their problems virtually and eliminate the troubles they could face during the foundry operations. They are usually the tools helping the foundry operations in design, cost analysis, design for casting, and process improvement [13]. Figure 5 shows a finite element analysis tool used for the solidification modeling and a gating design.

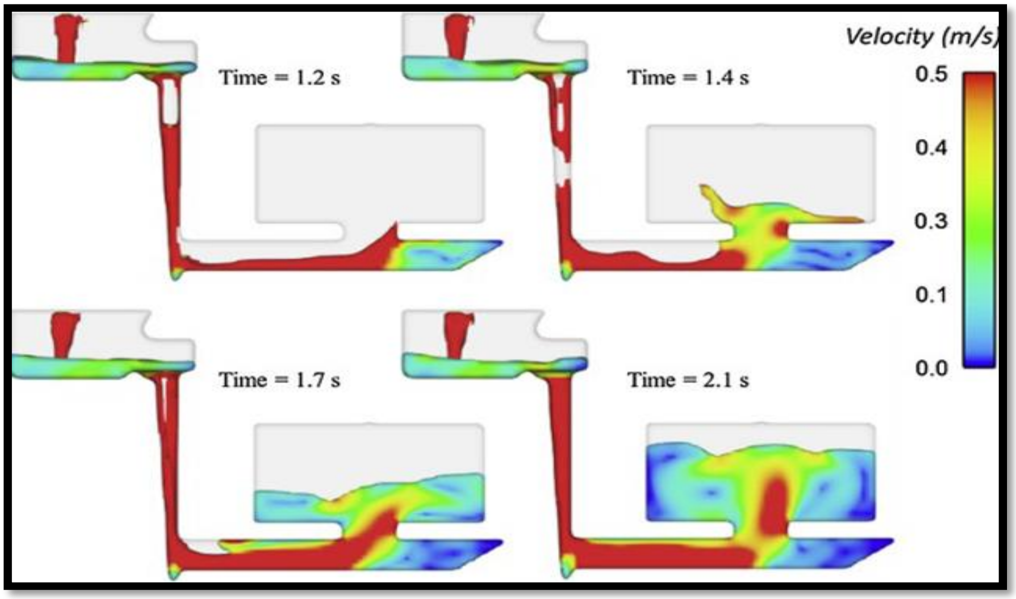


Figure 5: Sample Finite Element Analysis for a Gating System Design

Simulation Data

To effectively examine the effect of the UGT before utilizing it in foundry testing, a series of simulations were performed. First, the existing CAD model of the UGT and the tensile testing coupons were converted into a solid body and important into the casting simulation software, Inspire Cast. From here the CAD model was set up to function as a mold to be filled with Aluminum as shown in Figure 6. This is the same metal that will be used in later physical testing. The simulation was then run, and the data was analyzed. The simulation provides data on the flow of the liquid metal as it enters the mold cavity as well as showing any shrinkage or holes that may arise in the part as solidification occurs.

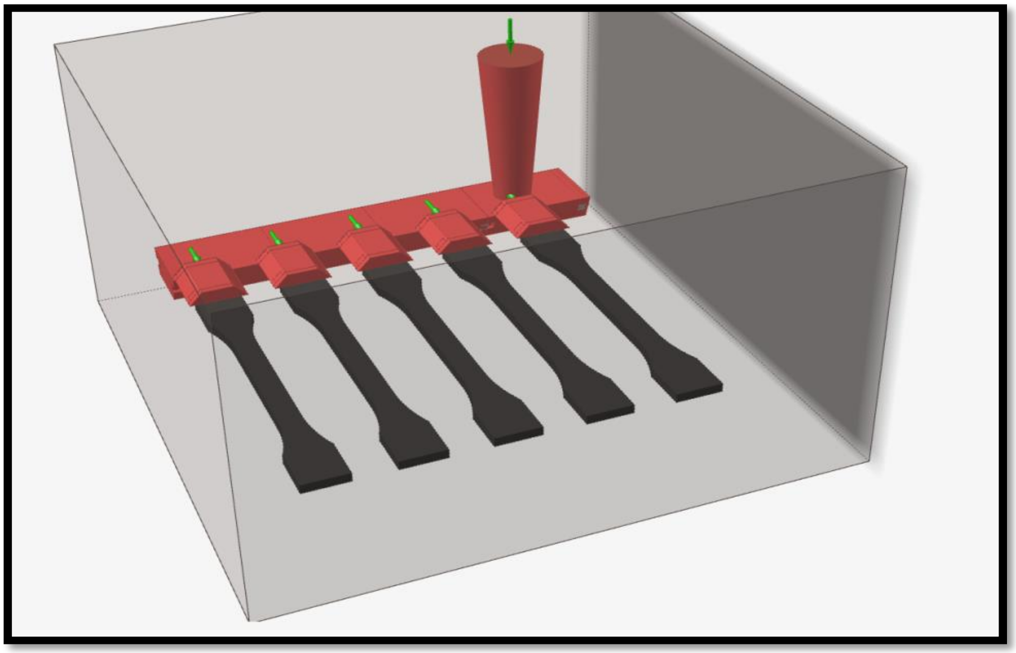


Figure 6. Set up of UGT for pouring and solidification simulations

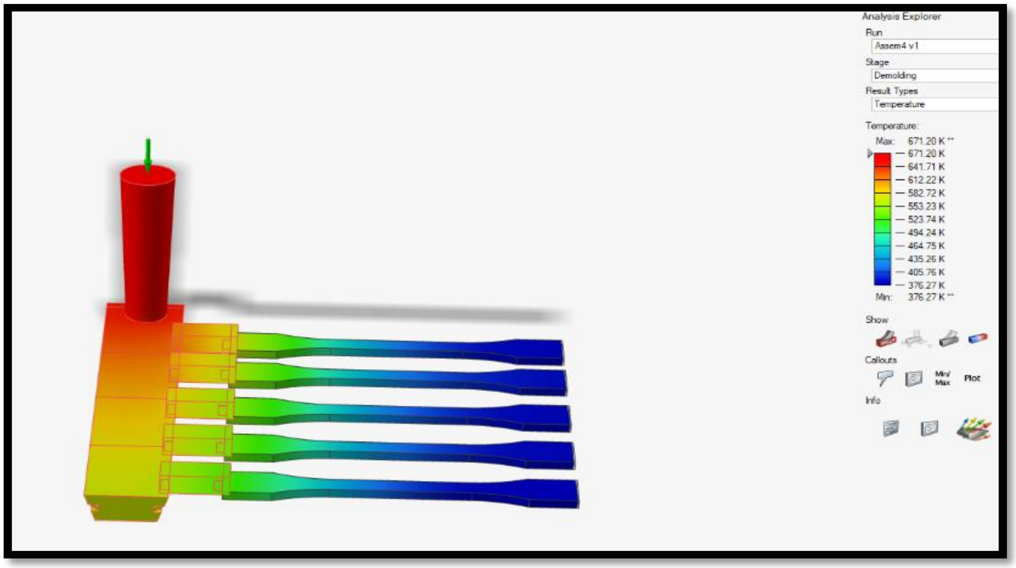
Results

By assessing the results of the simulation data, a few conclusions can be drawn regarding the quality of the castings using the UGT. By calculating the best gate size and number of gates for the casting, it is expected to see reductions in surface imperfections, holes, and shrinkage and so the simulation data will either confirm or refute the proposed results.

As indicated before, additive manufacturing specifics of the gating design, simulation, and fabrication are not reported in this work-in-progress study. The implication of the technology and its integration possibilities could be searched through [14][15][16][17][18].

Temperature Gradient

A standard gate system will distribute the heat of the molten metal through the whole mold with the entrance or sprue acting as the hottest point and the end of the pattern acting as the coldest spot in most applications. Based on the data shown in Figure 7, the UGT achieved its goal of properly distributing the heat. If the tool was poorly designed or the UGT dimensions were not correct, it would be expected to see cold shuts or areas that irregularly cooled, however, based on Figure 7, the part cooled uniformly showing the success of the UGT in distributing heat across the casting.



Analysis Explorer

Run: Assem4 v1

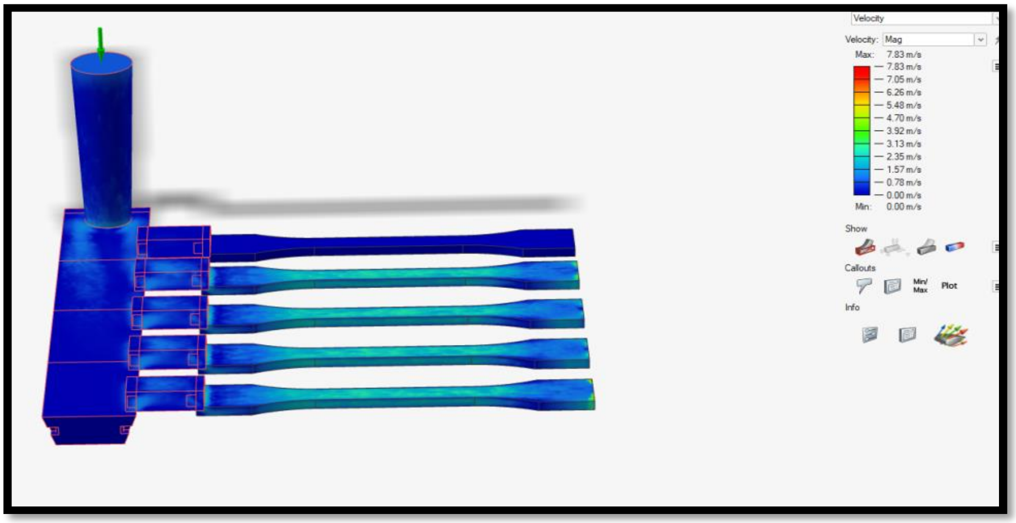
Stage: Demolding

Result Types: Temperature

Figure 7. Simulation results of the thermal gradient across the casting

Metal Velocity

One of the primary goals of the UGT dimensioning is to reduce the velocity as metal enters the mold to between 0.5 and 1.5m/s. much higher than this and the chance of defects increases and the quality decreases. Based on the initial simulations shown in Figure 8, the UGT accomplished this task reducing the entrance velocity of the metal to below 1.5m/s, however further into the mold the velocity of the metal increases to almost 2.35m/s. This could be the result of some light jetting of the metal as it enters the mold cavity. This will need to be addressed in later experiments.



Velocity

Velocity: Mag

Figure 8. Simulation results of the metal velocity of the casting

Sand Erosion

One of the most common issues with handmade gate systems is the issue of sand erosion. With this error case, the sand gets swept into the mold cavity by high-velocity metal and causes holes in the casting. This can be an extremely detrimental error in introducing into some parts. The simulation data in Figure 9 matches this expectation as the areas where a high velocity was previously seen there is also a higher level of sand erosion. However, the erosion overall is quite low which shows that the UGT completed its goal of reducing sand erosion. One area of note is that towards the end of the runner bar there is more erosion than any other area of the gating system. This means that the metal is bouncing off of this edge of the gate system. To fix this, later iterations should incorporate a longer runner bar or features such as a slag trap or a longer runner extension.

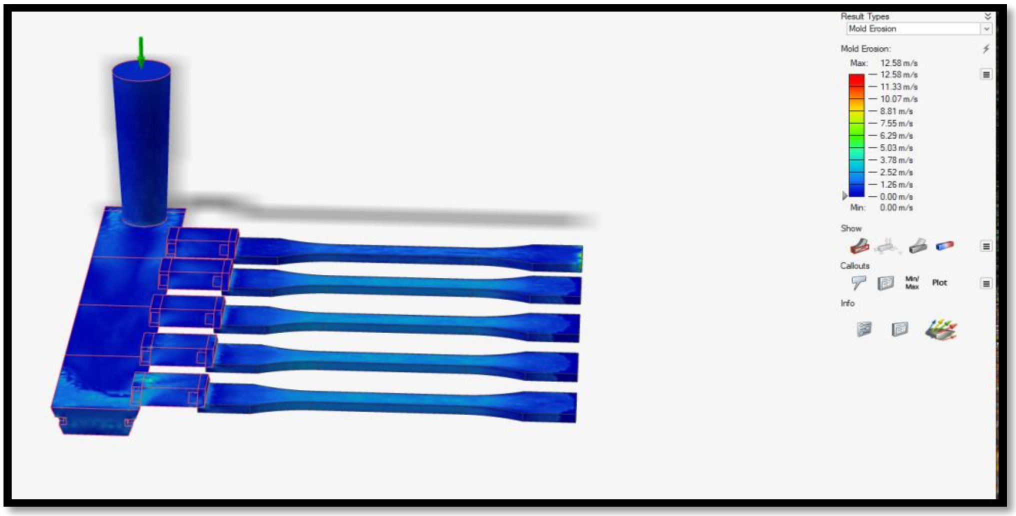

Result Types
Mold Erosion

Figure 9. Simulation results of sand erosion of the casting

Conclusions

Based on the analysis of the simulation data, the UGT has successfully met its objectives of reducing metal velocity to below 1.5 m/s and enhancing the surface quality of the casting. Future work in this research will involve empirical testing of the tool with physical castings, accompanied by a detailed examination of the components' microstructural and mechanical properties.

Acknowledgments

The financial and technical support provided by the Manufacturing and Engineering Technology Department of Tennessee Technological University made this research possible.

References

[1] T. Fresques, D. Cantrell, and I. Fidan, “The development of a framework between the 3D printed patterns and sand-cast work pieces,” *International Journal of Rapid Manufacturing*, vol. 5, no. 2, p. 170, 2015, doi: 10.1504/IJRAPIDM.2015.073575.

[2] M. Tanwir Alam *et al.*, “Optimization of Multi-Gate Systems in Casting Process: Experimental and Simulation Studies,” *IOP Conf Ser Mater Sci Eng*, vol. 404, no. 1, p. 012040, Aug. 2018, doi: 10.1088/1757-899X/404/1/012040.

[3] J. Campbell, *Complete Casting Handbook: Metal Casting Processes, Metallurgy, Techniques*, 2nd Edition. Elsevier, 2015. [Online]. Available: https://www.sciencedirect.com/book/9780444635099/complete-casting-handbook

[4] M. A. Khan, M. K. Ali, and M. Sajid, “Lean Implementation Framework: A Case of Performance Improvement of Casting Process,” *IEEE Access*, vol. 10, pp. 81281–81295, 2022, doi: 10.1109/ACCESS.2022.3194064.

[5] K. H. Renukananda, H. Khandelwal, and B. Ravi, “Influence of Gating Geometry Variations on Flow Balancing of Horizontal Multi-gate Systems in Casting,” *International Journal of Metalcasting*, pp. 1–18, May 2024, doi: 10.1007/S40962-024-01372-Y/TABLES/12.

[6] S. H. Majidi and C. Beckermann, “Effect of Pouring Conditions and Gating System Design on Air Entrainment During Mold Filling,” *International Journal of Metalcasting*, vol. 13, no. 2, pp. 255–272, Apr. 2019, doi: 10.1007/S40962-018-0272-X.

[7] T. Wang, X. Shen, J. Zhou, Y. Yin, X. Ji, and Q. Zhou, “Optimal Gating System Design of Steel Casting by Fruit Fly Optimization Algorithm Based on Casting Simulation Technology,” *International Journal of Metalcasting*, vol. 13, no. 3, pp. 561–570, Jul. 2019, doi: 10.1007/S40962-018-0291-7.

[8] M. Bruna and M. Galčík, “Casting Quality Improvement by Gating System Optimization,” *Archives of Foundry Engineering*, vol. 21, pp. 132–136, 2021, doi: 10.24425/afe.2021.136089.

[9] A. Modaresi, A. Safikhani, A. M. S. Noohi, N. Hamidnezhad, and S. M. Maki, “Gating system design and simulation of gray iron casting to eliminate oxide layers caused by turbulence,” *International Journal of Metalcasting*, vol. 11, no. 2, pp. 328–339, Apr. 2017, doi: 10.1007/S40962-016-0061-3.

[10] “U3 p2 riser design | PPT.” Accessed: Aug. 30, 2024. [Online]. Available: https://www.slideshare.net/slideshow/u3-p2-riser-design/47278545

[11] “Various Features in Casting.” Accessed: Aug. 30, 2024. [Online]. Available: https://www.slideshare.net/slideshow/casting-1404036/1404036#7

[12] F. Y. Hsu, M. R. Jolly, and J. Campbell, “A multiple-gate runner system for gravity casting,” *J Mater Process Technol*, vol. 209, no. 17, pp. 5736–5750, Aug. 2009, doi: 10.1016/J.JMATPROTEC.2009.06.003.

[13] “Analysis of solidification process of sand casting.” Accessed: Aug. 30, 2024. [Online]. Available: https://www.zhycasting.com/analysis-of-solidification-process-of-sand-casting/

[14] I. Fidan *et al.*, “Recent Inventions in Additive Manufacturing: Holistic Review,” *Inventions 2023, Vol. 8, Page 103*, vol. 8, no. 4, p. 103, Aug. 2023, doi: 10.3390/INVENTIONS8040103.

[15] I. Fidan *et al.*, “Nano-Level Additive Manufacturing: Condensed Review of Processes, Materials, and Industrial Applications,” *Technologies 2024, Vol. 12, Page 117*, vol. 12, no. 7, p. 117, Jul. 2024, doi: 10.3390/TECHNOLOGIES12070117.

[16] F. Alifui-Segbaya, I. F. Ituarte, S. Hasanov, A. Gupta, and I. Fidan, “Opportunities and Limitations of Additive Manufacturing,” *Springer Handbooks*, vol. Part F1592, pp. 125–143, 2023, doi: 10.1007/978-3-031-20752-5_9.

[17] I. Fidan *et al.*, “The trends and challenges of fiber reinforced additive manufacturing,” *International Journal of Advanced Manufacturing Technology*, vol. 102, no. 5–8, pp. 1801–1818, Jun. 2019, doi: 10.1007/S00170-018-03269-7.

[18] S. Hasanov *et al.*, “Review on Additive Manufacturing of Multi-Material Parts: Progress and Challenges,” *Journal of Manufacturing and Materials Processing 2022, Vol. 6, Page 4*, vol. 6, no. 1, p. 4, Dec. 2021, doi: 10.3390/JMMP6010004.