Solid Freeform Fabrication 2024: Proceedings of the 35th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Mold Design using Binder-Jetted Sand for Aluminum Casting

Jacob Rodriguez[1,2] Cristian Bañuelos[1,2] Eduardo Barrios[1] Denise Rojas- Melendez[1,2] Shadman Tahsin Nabil[1,2] Christopher J. Danek[1] Bob Wood[3] Fransisco Medina[1,2]

[1] Department of Aerospace and Mechanical Engineering, University of Texas at El Paso, El Paso, TX, 79968, USA

[2]W.M. Keck Center for 3D Innovation, University of Texas at El Paso, El Paso, Tx, 79968, USA

[3]ExOne: North America Research Center 66850 Executive Drive St. Clairsville, OH 43950, USA

Keywords: Additive Manufacturing, Aluminum alloy, Sand Cast, Binder-jetting, silica sand

Abstract

The purpose of this project is to design a mold in collaboration with ExOne, for a helicopter ejection handle. The mold will be printed using binder jetting 3-D printing technology, made of silica sand, and will be cast using Aluminum A356. Throughout the project the team collaborated with various members of ExOne, who provided feedback and suggestions in improvements on mold design, and were guided in importance of parting lines, minimum thickness of part, and many other important factors to consider for casting. Weekly meetings with employees from ExOne were conducted, as well as team meetings to discuss mold design and casting practices. As prototypes were cast using scrap metal, simulations for strength of the handle, solidification analysis, and tensile tests were conducted with the cast metal. Two final iterations were created, a horizontal and vertical mold which were cast and analyzed. The horizontal mold proved to be the most successful when casting, with almost no area's left unfilled.

Introduction

Metal casting has existed for thousands of years; today, this process plays a key role in the manufacture of anything from simple household items to complex geometries in the automotive and aerospace industries. Aluminum alloys are widely used in the industry(Nabil et al., 2022). As the field of engineering continues to grow, innovative technologies can be used to improve casting processes. Traditional casting is limited to how complex geometries can be, as well as low dimensional accuracies. Labor to make mold packages for traditional casting can be intensive. Additive manufacturing has already been introduced to this ancient technology with the intention to improve complexity of geometries, reduce waste and labor time, and to optimize the process. This project highlights how binder jetting, an additive manufacturing technology, has revolutionized traditional sand casting.

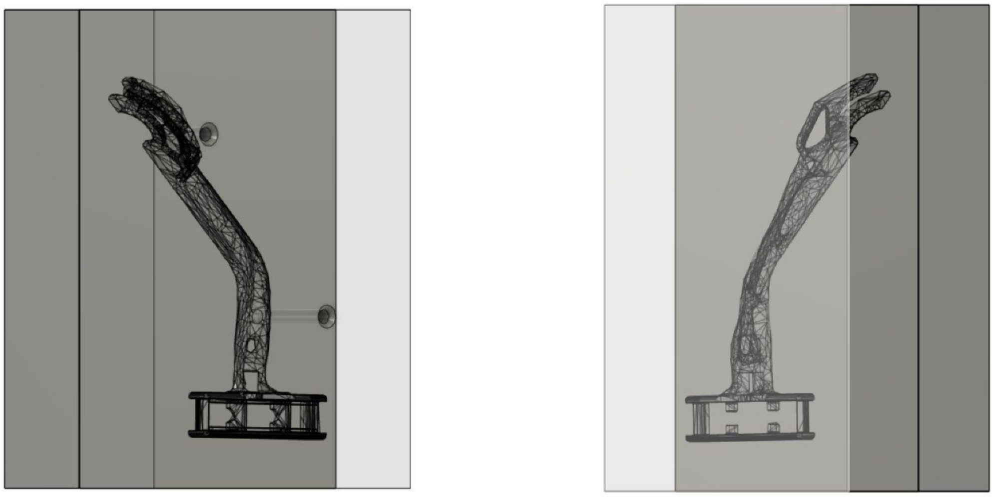
Tasked with developing sand molds for an ejection handle, whose geometry had been optimized with the intent of 3d printing with military-grade aluminum A357. After researching the process of metal casting and 3d printed sand molds through various case studies, articles (Appendix 1) and receiving feedback from ExOne and other industry experts, it was determined that the geometry of the handle needed to be modified. The original piece contained features that could not be captured during the mold design process due to sizing constraints. The geometry of the handle was modified and tensile tested using Autodesk Fusion, a Computer-Aided Design (CAD), and Finite Element Analysis (FEA) software, to generate two mold iterations in horizontal and vertical orientations. Solidification and mold flow analysis were then performed on the mold iterations. Mihaela Nastac from ExOne assisted with the analysis of the vertical mold iteration using NOVA Flow & Solid, a casting software used in the industry, while the simulation for the horizontal orientation was performed using Ansys Fluent, a Computational Fluid Dynamics (CFD) program, available to the team, licensed by the university.

A process to determine the functionality of the molds needed to be developed. With the approval of the department, an order for a propane furnace and aluminum a356, similar to a357(*A356.0 Aluminum vs. A357.0 Aluminum :: MakeItFrom.Com*, n.d.), was placed. Hoosier Pattern, a customer of ExOne, provided practice molds for the team to inspect and become familiar with printed sand molds and to aid with the practice castings. The final casting was performed using the aluminum a356 which was melted in a propane furnace and poured into the molds designed for the handle. Tensile testing and microstructure comparison were conducted on features of the final part cast with aluminum a356 with published papers regarding cast aluminum a356.

Methods

Mold Design Rapid Innovation

It was required to design a mold package for the given Ejection Handle geometry. The geometry that was provided to the team, had been through a topology optimization which gave it a complex organic look. An initial design concept was developed, which consisted of two pieces that are denoted as the cope and drag components(liu, 2009). The cope was the piece that contained the initial design of the rigging and gating system (Figure 1a). The rigging and gating system consisted of two cylinders in the upper area and lower area of the Ejection Handle. This initial design was meant to give the team a glimpse of working with mold design on Autodesk Fusion 360.



(a) (b)

Figure 1: 30% Opacity of Cope component (a) and 30% opacity of Drag Component (b)

After discussion, it was concluded that the optimized version of the ejection handle will not be ideal when it comes to mold design and metal casting. This led to the agreement to modify the geometry. To properly capture details within mold designs, the minimum thickness of any feature should not be less than 4 mm for any 3D model so that the jet binding process can capture every detail in the design. Any features within mold designs with a thickness smaller than 4 mm can lead to improper flow of liquid metal, leading to a potential failure of the casting. A proper STEP file is also required for multiple reasons. Some of those reasons include implementing specific material properties to properly simulate any design and receive accurate results. Other reasons include the ability to modify the 3D CAD design to pursue different iterations without having to start from the beginning every time a change needs to be made. Lastly, to have a file with solid properties so mold design can be based on the CAD model that is requested to be casted. The initial file provided to the team was an .STL file which made it difficult to capture mold design and simulate the process. To combat this, the ejection handle was re-designed and modified. The minimum thickness found on the geometry was increased to 4 mm. The topology optimization found in the geometry was eliminated, reducing the complexity. This gave the geometry a more industrial look and was used to move forward with and begin designing mold concepts. In comparison to the initial geometry, the redesigned part came to have more industrial features and less complex surfaces while keeping the vital features that were unique to the requested part. Comparing Figure 2(a) and Figure 2(b), the part will be cast with the intent to have a minimal thickness of 4mm and for surfaces to maintain a more simplistic design. Figure 1(a) represents the attempted mold design using the initial part concept with complex geometry. It should also be noted the difficulty in mold design since the file provided was an STL file, giving no physical properties to the part in the CAD software. This prevented the geometry from designing a mold around the part. With the final part concept file having physical properties and meeting the 4mm thickness minimum, it was decided to take upon two different design concepts to compare the ability of casting processes. The two concepts were defined as horizontal and vertical orientations

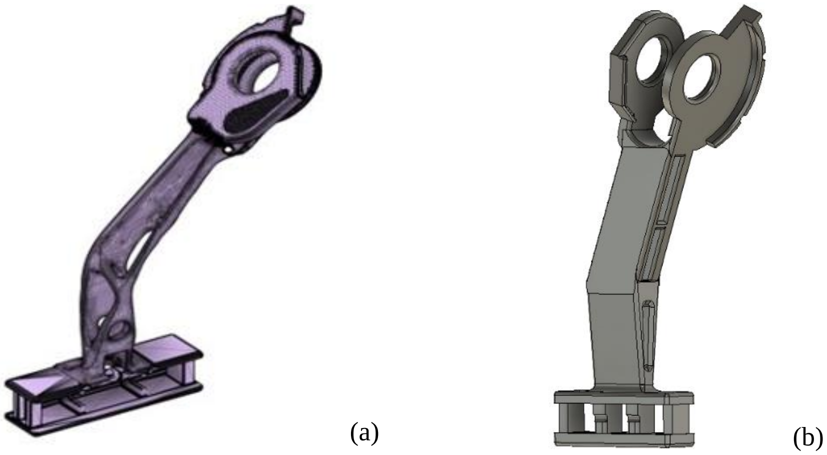

(a) (b)

Figure 2: Initial Part Concept (a). Final Part Concept (b).

With this more industrial design, mold package designs began. The printed mold packages were provided by Hoosier patterns. After obtaining approval for the modified version of the ejection handle, two distinct concepts were developed. These concepts are outlined as vertical orientation and horizontal orientation. The two different concepts allowed the team to compare the effect of the orientation of the geometry within the molds. The preliminary design iteration's vertical orientation (Figure 3) consisted of a multiple-piece concept with a total of five pieces. The feedback received disclosed that complexity would increase due to the many parting lines(liu, 2009) that were incorporated, which would make the cleaning of the molds after printing rather difficult. Feedback received on this iteration defined the mold as being too complex, especially when it comes down to the assembly. Feedback recommended to decrease the number of parting lines to one.

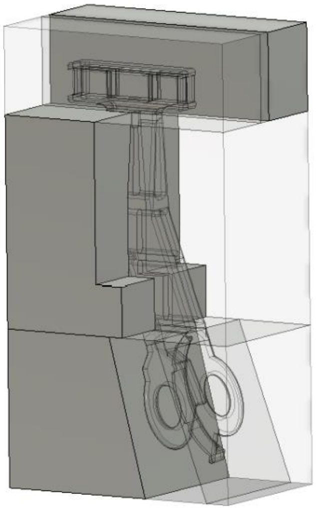


Figure 3: Preliminary design of vertical orientation with excessive parting lines.

The horizontal orientation of the preliminary design iteration introduced a pie-shaped mold (figure 4). This was inspired by mold design samples that were provided by stakeholders. This iteration consisted of additional parting lines, and two cylindrical features that would serve as rods to hold all the pieces in place. The placement of the parting lines would not allow access to intricate features such as the top round features of the geometry for cleaning. The vertical orientation concept reduced its number of parting lines to one, compared to the previous iteration; the parting line was placed in a way that would allow access to the features as previously discussed. Complex features such as the top circular features of the geometry should be attached to either the cope or drag of the mold. A core component should be designed to capture the center features (hollowed areas). It was also recommended to add draft angles(*Draft Angle - an Overview | ScienceDirect Topics*, n.d.) to the connection between the two pieces of the mold to aid with the assembling of the mold.

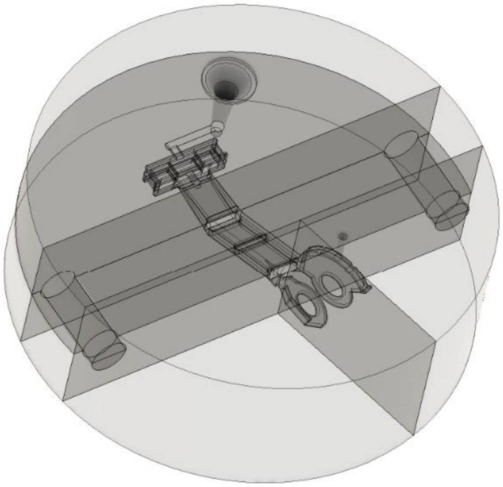


Figure 4: Preliminary design of Horizontal Orientation.

A rigging and gating system(liu, 2009) design was then added to the next iterations of both the horizontal and vertical concepts. The horizontal orientation's rigging and gating system consisted of a hemi spherical shaped pouring basin, a cone-shaped sprue, cylindrical shaped well runners and vents, and rectangular-shaped gates as seen in **Figure 5**(liu, 2009). The gates were connected to the lower end of the geometry, and the vents were attached to the circular features at the top of the geometry. The vertical orientation's rigging and gating system had a more rectangular-shaped attribute as seen in **Figure 6**. The gates were also connected in the lower area with the vents being at the top of the geometry. These particular shapes within the combination of the rigging and gating components were defined as ideal by the research conducted on the topic.

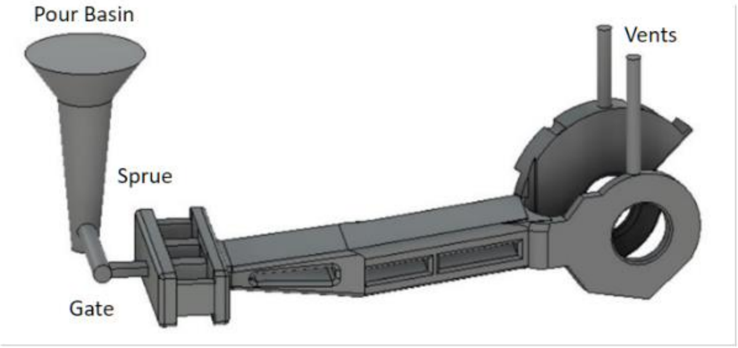


Figure 5: Rigging and Gating system for Horizontal Orientation.

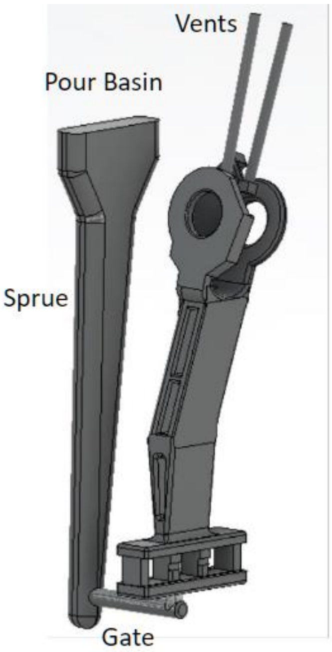


Figure 6: Rigging and Gating System for Vertical orientation.

Simulations

A solidification analysis software was used to clarify the components that were chosen for this design. The vertical orientation was analyzed compliments of experts from ExOne, and the horizontal orientation was analyzed by using ANSYS software. The process of this solidification analysis consisted of creating a mesh of the geometry, and the implementation of property parameters to the set-up of the simulation. The mesh and the set up are vital in order to obtain proper and accurate results of the simulation. The mesh (Figure 1) geometry was created using the body fitted cartesian method with an element size of 0.001 m. This meshing method generated about 207,000 elements, acquired an average element quality of 0.91, and an average aspect ratio of 1.415. All of which are adequate parameters for a mesh.

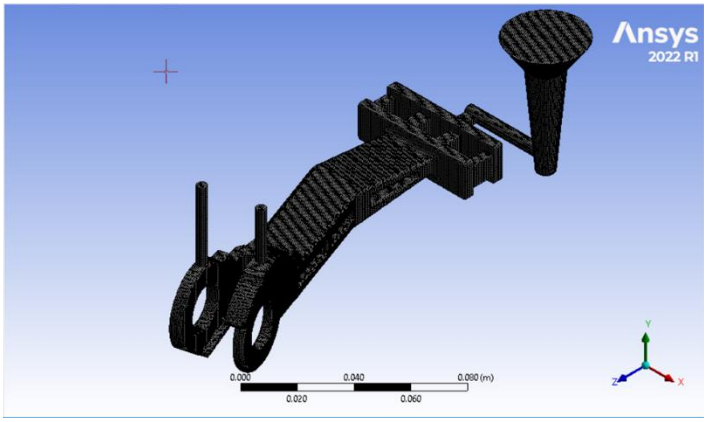


Figure 7: Mesh results of Horizontal Orientation.

The set up for this solidification analysis defined a pressure-based solver type, an absolute velocity formulation, transient, with a gravitation acceleration of -9.81 m/s^2 in the negative y-direction. The fluid materials consisted of A356.0-T6 (metal liquid) and air. The only solid material was defined as sand mold. Table 1 depicts the properties that were implemented for A356.0-T6(*Aluminum A356.0-T6, Sand Cast*, n.d.).

Table 1 A356.0-T6 Properties

Density [kg/m^3]	Cp [J/(kg-K)]	Thermal Conductivity [W/(m-K)]	Viscosity [kg/(m-s)]	Pure Solvent Melting Heat [J/kg]	Solidus [K]	Liquidus [K]
2600	963	151	0.001	397500	830.15	886.15

The density of the sand mold was calculated to be 453.59 [kg/m^3]. Specific Heat and Thermal Conductivity properties were implemented on to the set up as piecewise-linear functions as seen in Figure 2. (Saeidpour et al., 2022)

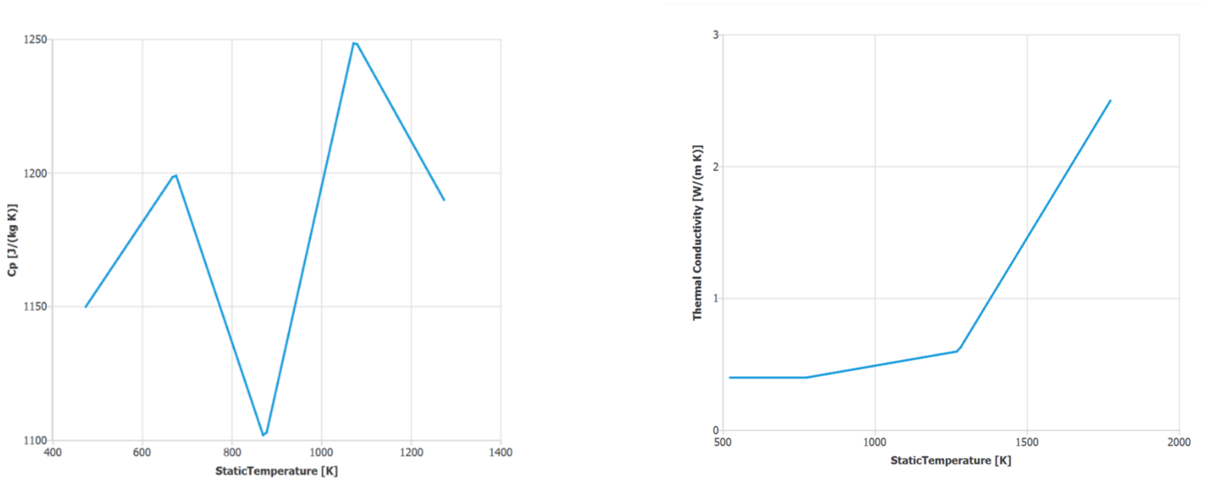


Figure 8: Specific Heat of Sand Mold Parameters (a) Thermal Conductivity of Sand Mold Parameters(b)

Boundary conditions were set as the pouring basin face being the inlet, the entire geometry as a solid wall, and the two attached cylindrical vents as the outlets. The inlet was defined as velocity-inlet type in a liquid phase with a velocity magnitude of 0.5 m/s and temperature of 1008.15 [K]. The solid wall zone was set up to have convection thermal conditions with a heat transfer coefficient of 20 [W/m^2-K]. The outlets were defined as pressure-based outlets. The solution of the simulation was set up to be calculated in a simple scheme with 500-time steps with 20 iterations per time step.

Results

Final Design Concept

When initially designing the molds, a more complex approach on each iteration. At the beginning, the vertical design iteration of the mold was designed to be a five-piece mold. For initial horizontal iterations, the design had the same idea applied which also resulted in multiple pieces to complete the mold design. After receiving feedback from our champion, it was decided that these iterations had too many parting lines as shown in Figure 3 and Figure 4. Through this feedback, the vertical mold design became simplified to a 2-piece mold generating only one parting that formed more into a jigsaw puzzle type pattern. The final design for the vertical concept (Figure 9) took draft angles into consideration and two spherical pins were added to the center outer area of the mold to assist with keeping the two pieces in place. Holes were added in each corner of the mold pieces to allow for the placement of a screw to hold the two pieces together. The rectangular look was kept for the rigging and gating system since promising results were obtained from the solidification analysis.

The horizontal mold iteration was simplified to a 2-piece part that also included a core. Some extra features were added into the final design of the horizontal orientation (Figure 10). Extrusions were added to both the cope and drag of the mold on altering areas to aid with capturing the circular features of the geometry. A core component was implemented to acquire the hollow areas in the center of the ejection handle, which is located between the two larger mold pieces. Two elongated cone shaped pins were added to the cope to keep the mold pieces in place when assembled. Holes were added on each corner of the cope and drag to facilitate the addition of screws to hold all the pieces together. Although a solidification analysis was unable to be processed for the horizontal concept at the time, the team decided to stay with the initial design of the rigging and gating system. This was largely due to deadlines that needed to be met to be able to obtain the 3D printed mold designs on time.

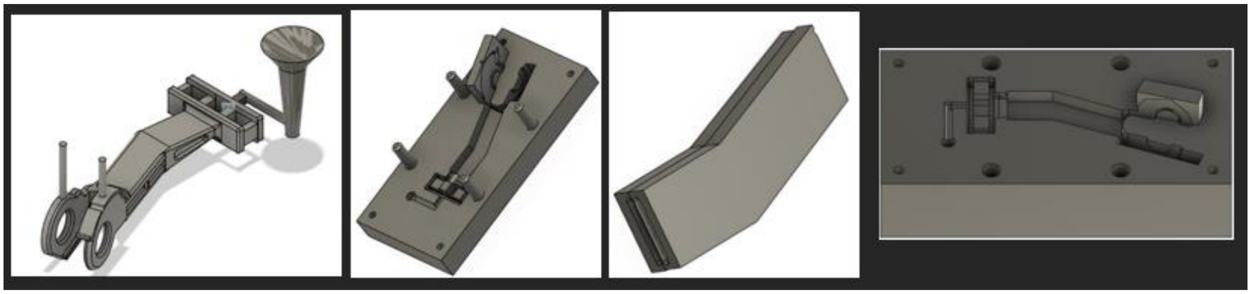


Figure 10: Final Design of Horizontal Orientation

Engineering Results

The team received the 3D Printed Sand Molds. The molds were received without any post processing (cleaning). The method used in the printing of sand molds introduces sand in hollow areas, the team needed to clean out the sand prior to the assembly of the mold pieces. After the cleaning of the molds was completed, the team then had to assemble all pieces and secure them together with nuts and bolts.

Figure 11: Result of 3D Printed Sand Molds if both vertical and horizontal concepts before cleaning process

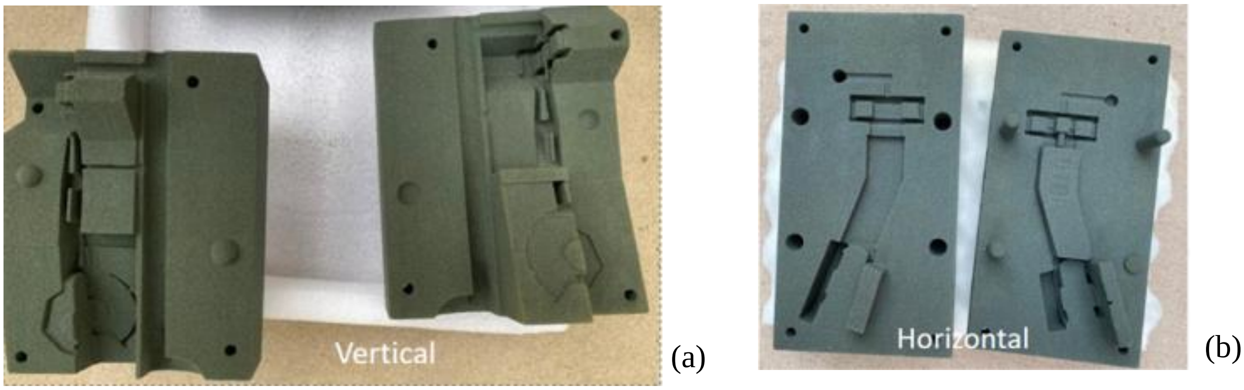
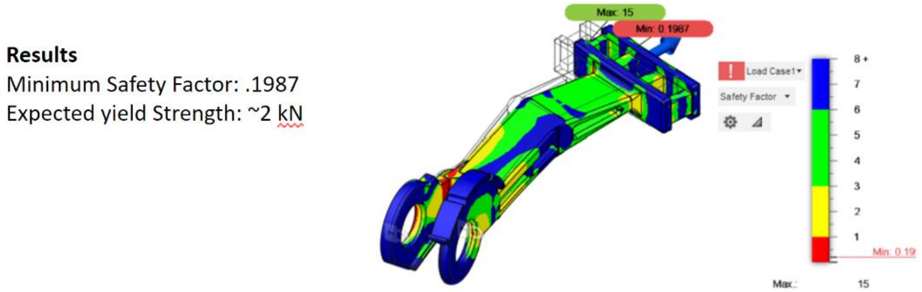


Figure 12: Result of 3D Printed Sand Molds after cleaning process: (a) and (b)

Simulation Results

A solidification analysis software was used to clarify the components that were chosen for this design. The vertical orientation was analyzed compliments of experts from ExOne, and the horizontal orientation was analyzed by the team using the ANSYS software. The process of this solidification analysis consisted of creating a mesh of the geometry, and the implementation of property parameters to the set-up of the simulation. The mesh and the set up are vital in order to obtain proper and accurate results of the simulation. The mesh (**Figure 7**) geometry was created using the body fitted cartesian method with an element size of 0.001 m. This meshing method generated about 207,000 elements, acquired an average element quality of 0.91, and an average aspect ratio of 1.415. All of which are adequate parameters for a mesh

A Fusion 360 Static Stress simulation with the handle constrained at the circular features of the geometry, and a load applied outward yielded results seen on Figure 13.

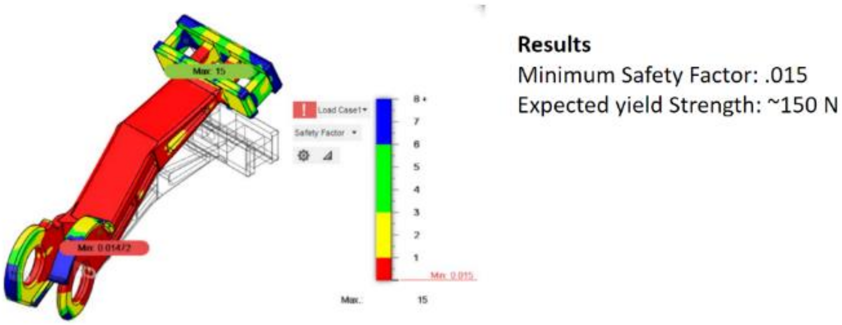


Results
Minimum Safety Factor: .1987
Expected yield Strength: ~2 kN

Figure 13: Fusion 360 Static Stress Outward Load

The simulation of the outward load resulted in the geometry to have a Factor of safety rating of 0.1987 and an expected yield strength of 2 kN.

A Fusion 360 Static Stress simulation with the ejection handle constrained at the circular features of the geometry, and a load applied upward yielded results seen on Figure 14.



Results
Minimum Safety Factor: .015
Expected yield Strength: ~150 N

Figure 14: Fusion 360 Static Stress Upward Load

The simulation of the upward load resulted in the geometry to have a Factor of safety rating of 0.015 and an expected yield strength of 150 N.

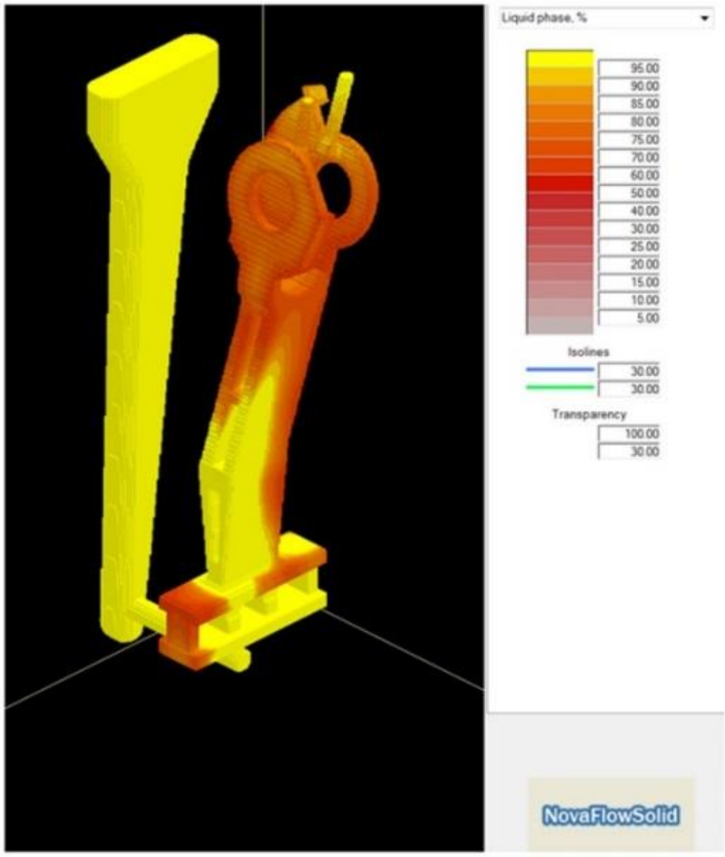
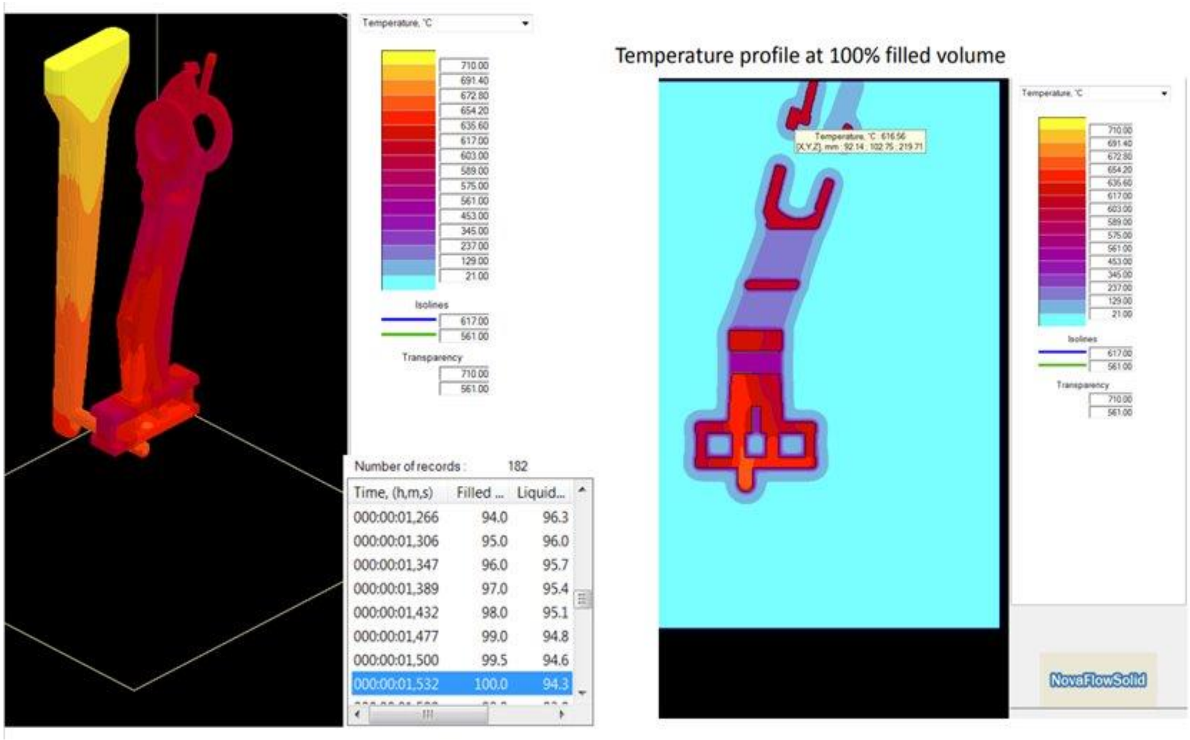


Figure 15: Vertical Casting Liquid Phase Simulation Results


Temperature profile at 100% filled volume

Temperature, °C : 616.56
[X,Y,Z], mm : 92.14 ; 102.75 ; 219.71

Number of records : 182

Time, (h,m,s)	Filled ...	Liquid...
000:00:01,266	94.0	96.3
000:00:01,306	95.0	96.0
000:00:01,347	96.0	95.7
000:00:01,389	97.0	95.4
000:00:01,432	98.0	95.1
000:00:01,477	99.0	94.8
000:00:01,500	99.5	94.6
000:00:01,532	100.0	94.3

Figure 16: Vertical Casting Temperature

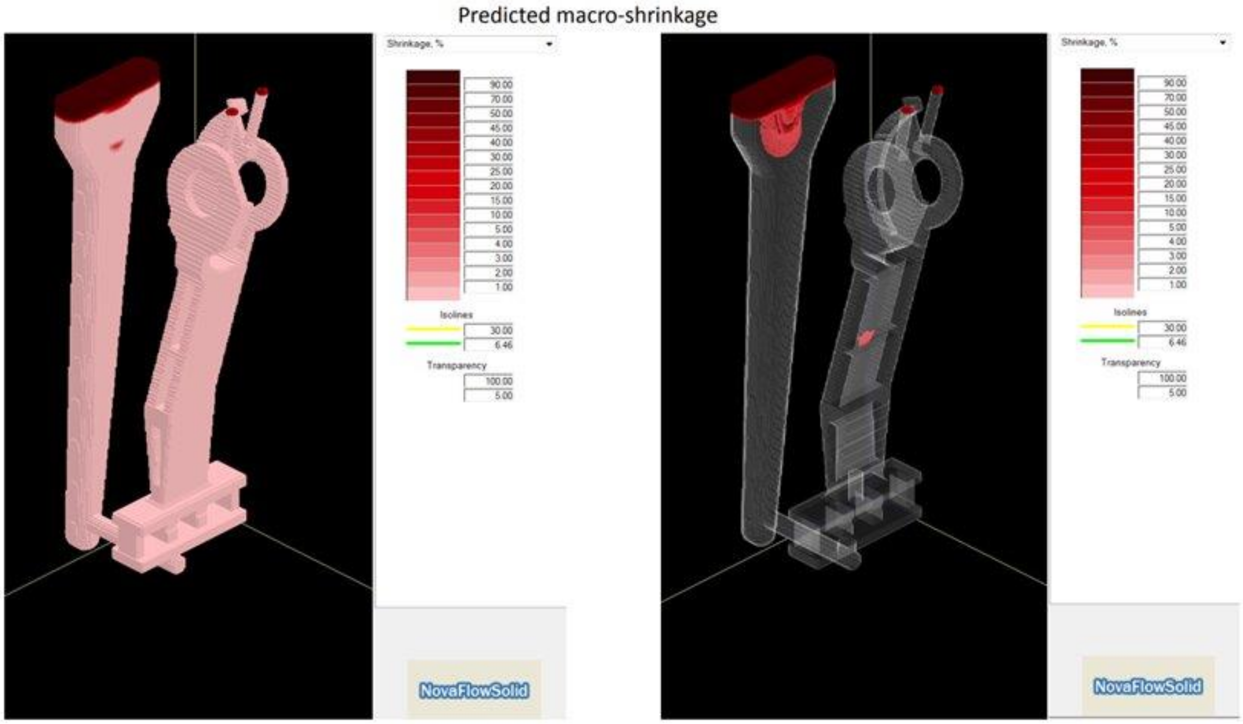

Predicted macro-shrinkage

Figure 17: Macro Shrinkage Simulation Results

Analyzing the Nova Flow Solid simulations provided by ExOne, it was observed that areas that would have difficulty filling are the upper regions of the circular portions near the vents. A second gate was then added to the rigging and gating system aid in cast filling, displayed in **Figure 18.**

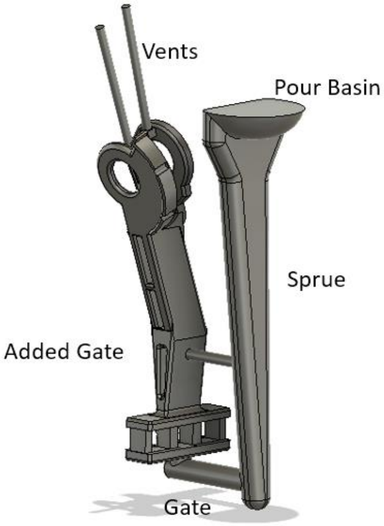


Figure 18: Added gate to vertical rigging and gating system.

A solidification analysis was conducted on the vertical orientation concept and yielded the following results seen on Figure 19 – Figure 20

Similar simulations were conducted on the horizontal orientation using ANSYS software. The following figures disclose the results.

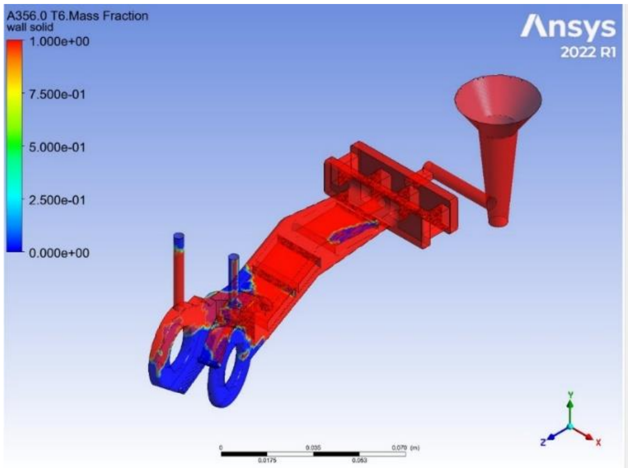


Figure 19: Horizontal Casting Mass Fraction Simulation Results

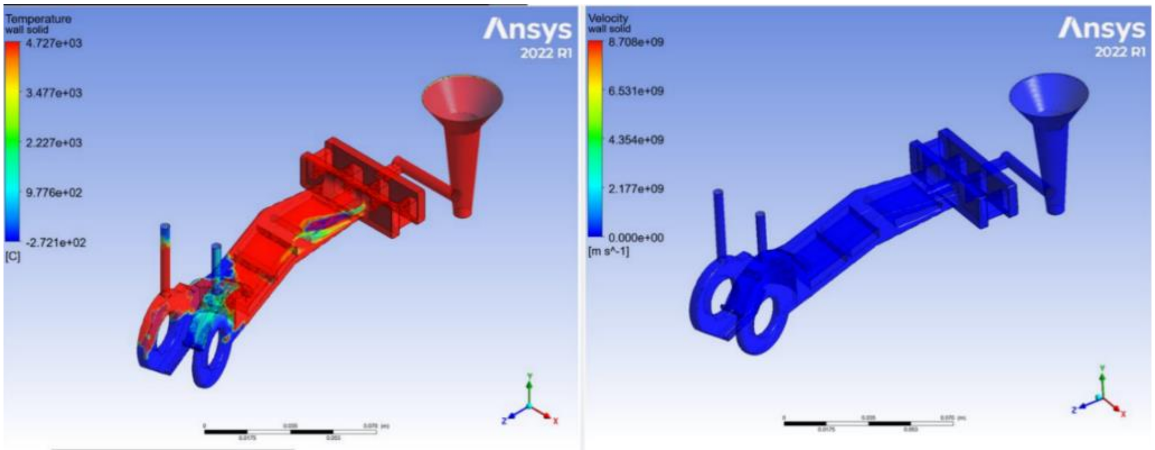


Figure 20: Horizontal Casting Temperature and Flow Velocity Simulation Results

The simulations performed on Ansys resulted in temperature around circular regions to be colder than the rest of the cast indicating that those regions may have difficulty filling. Flow Velocity results may indicate a failed simulation. Due to time constraints, further analysis of Flow Velocity simulations would be considered for future work.

Final Casting Results.

Upon the final casting operations, the entire process was a success in terms of Risk Controls, Propane furnace working properly, and reaching optimal temperature in melting the alloy. The outcome of the final cast however was not complete due to the molds not being filled completely. In reference to the results, Figure 21 is derived from two molds (one of each iteration) that did not break prior to the final casting operations.

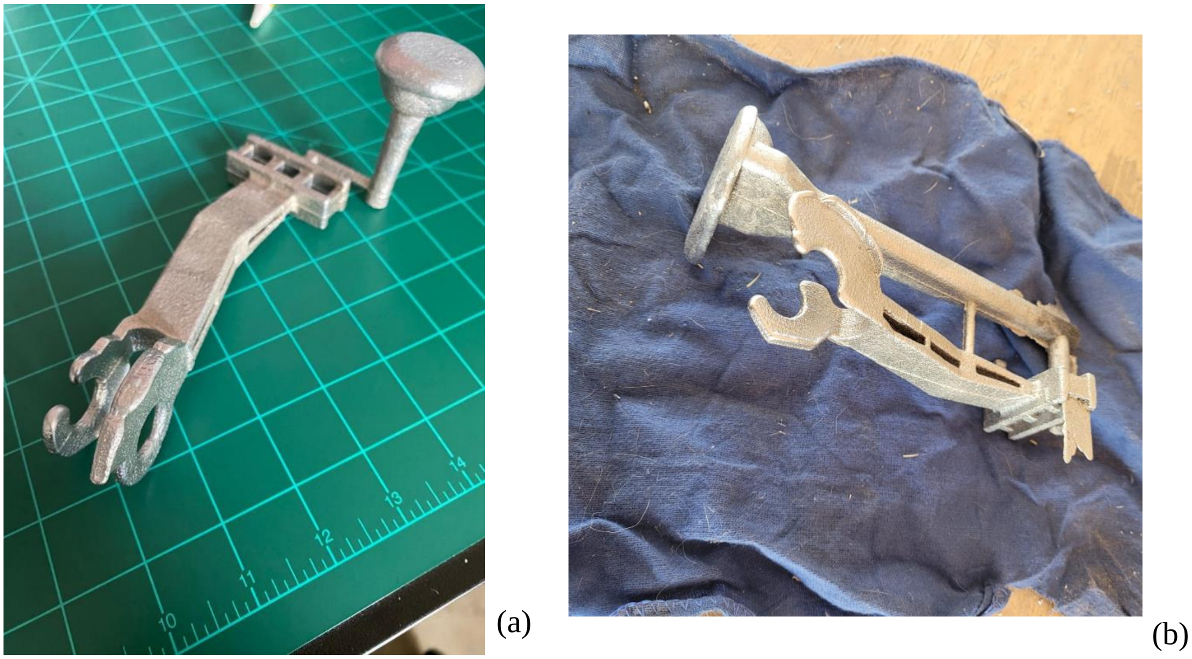

(a) (b)

Figure 21: Horizontal Iteration Final Cast (a) Vertical Iteration Final Cast (b)

Tensile testing conducted on the Aluminum A356 sprue specimens produced the results seen on Figures 23.

Legend	No.	S_0 mm²	m_E GPa	$R_{p0.2}$ MPa	R_{eH} MPa	R_m MPa	A_g %	A_{gt} %	R_B MPa	$A_{23,13mm}$ %	A_t %
🟧	3	30.88	60.2	113	-	149	0.9	1.1	143	0.9	1.1

Series graph:

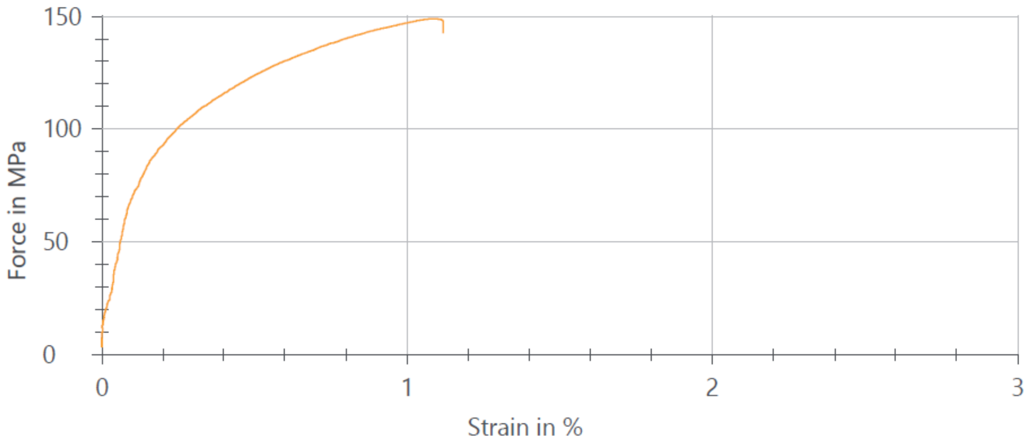


Figure 23: Aluminum A356 Sprue Tensile Testing Results

R_m represents the tensile strength of the specimen, with a value of 149 MPa. R_B represents the shear strength, with a value of 143 MPa. $R_{p0.2}$ represents , with a value of 113 MPa. The tensile modulus is represented by m_E, with a value of 60.2 GPa. A_g and A_t both reflect a value of 1.1% in strain.

In reference to mechanical properties of traditional sand cast aluminum A356, where the tensile strength is listed as “>=165 MPa at 0.2%”.(*Aluminum A356.0-T6, Sand Cast*, n.d.) The shear strength listed as “143 MPa” and the Tensile modulus listed as “72.4 GPa”.(*Aluminum A356.0-T6, Sand Cast*, n.d.)

A tensile test was performed on a study of creep behavior of aluminum A356 being reinforced with multi-walled carbon nanotubes by stir casting. In the comparison to the **Figure 23** a similar curve trend can be seen on and the Stress-Strain diagram of A356 alloy stir casting without carbon nanotube reinforcement provided for the study in the Figure below. The similar trend is represented by the blue slotted line. The ultimate Tensile strength for the stir “casted A356 was reported as 124 MPa at 0.2% elongation.” (Tan et al., 2022)

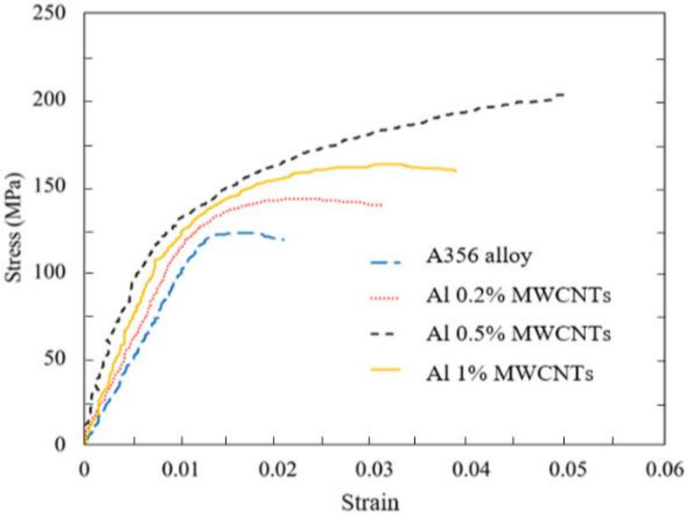
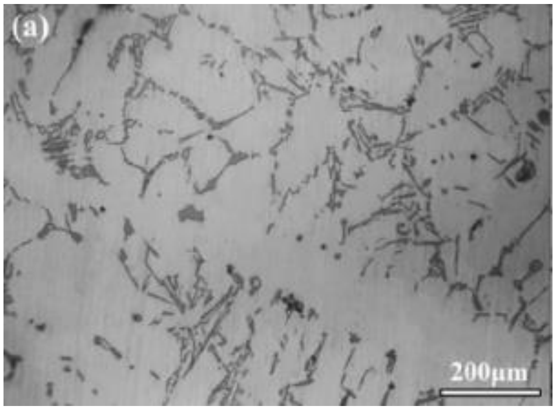
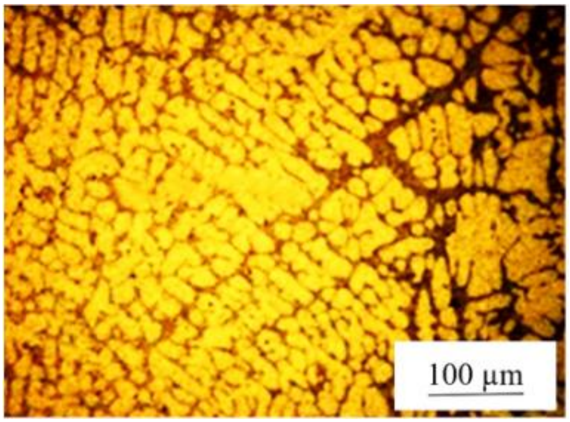


Figure 24: The stress–strain diagram of A356 aluminum alloy and nanocomposites containing 0.2%,0.5%, and 1% MWCNT addition. (Tan et al., 2022)

Microstructure of Al-A356 Compared



(a)



(b)

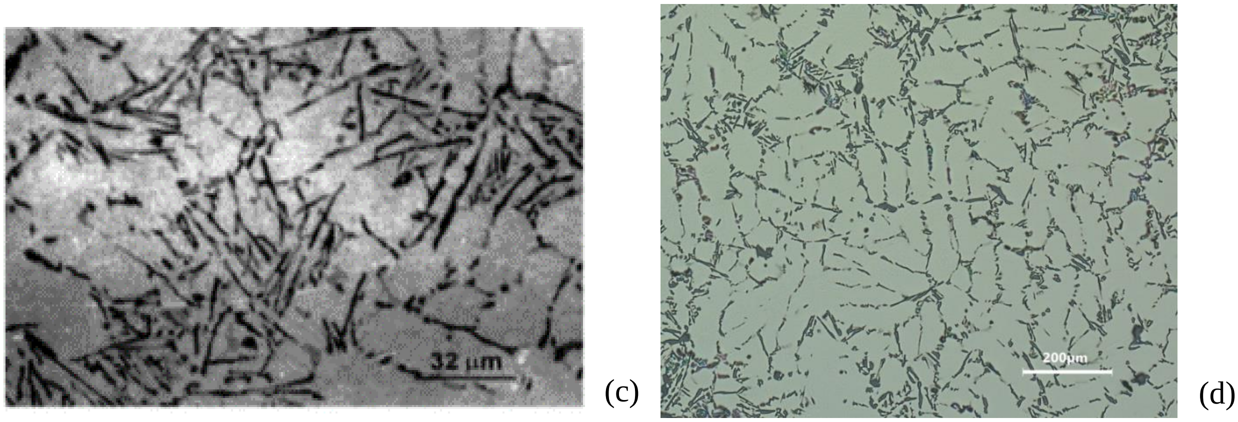


Figure 25: “Microstructure of Al A356 Cast studied with vibration frequencies at 0Hz” (Jiang et al., 2015)(a), “Typical optical images of Al A356 alloy” (Tan et al., 2022)(b) Typical microstructure of permanent mold cast specimens (As-cast condition) (Shabestari & Shahri, 2004)(c) and microstructure of AL A356 casted ejection handle.(d)

In **Figure 25 (a),** represents the microstructure of AlA356 alloy that was studied for the effects vibration frequencies can have on the microstructures of a cast alloy. It was observed after cast operations implemented 0 Hz of frequency. Comparison between **Figure 25(a,b,c, and d)** demonstrates the similarities in cast microstructures of alternate casting methods. A trend of non-uniform distribution of primary α-Al phase with slightly denser areas of eutectic phases showcases that the benefits of AM technology can be applied to metal casting technology while retaining the properties that make metal casting a favorable method of manufacturing.

Discussion

To perfect the mold design, a rapid innovation approach was introduced, where multiple designs were provided to stakeholders on a weekly basis. The feedback received allowed to further understand and learn the technicality behind mold designs. The process of learning mold design also assisted with the justification behind restrictions such as complexity of geometry and minimum thickness of features. Practice molds provided by ExOne helped the team understand how to safely conduct casting procedures and the Personal Protective equipment needed to prevent injury.

Static stress simulations, and tensile testing were conducted to understand the properties of A356 aluminum casts and compare with traditional Cast methods of the alloy. The team will be able to analyze the effect the type of aluminum has on 3D Printed Sand Molds. Due to time constraints, this was not able to be accomplished, however it is being considered for future work.

The solidification analysis on the vertical orientation that was provided by professionals from ExOne did turn out to be accurate compared to our final casting results. The incompleteness of the final castings is largely due to improper flow introduced into the mold by the metal casting operator. The simulations conducted on the horizontal orientation were not as accurate unfortunately, this was expected since there was lack of access to sophisticated software such as the one that was used for the vertical orientation. ANSYS was utilized with very minimal guidance and information on how to properly run solidification analysis simulations. Part of the future work is to conduct further research and refine the results that were obtained in the simulation.

Conclusions

After observing the results obtained from the final casting operations, the horizontal iteration of mold design happened to have more completion in filling the mold as opposed to the vertical iteration. This resulted in both the complete intact moldings and the moldings that had broken sections prior to the final casting operations, contrary to the results provided from the simulations. It was concluded that various reasons took part in why the filling was not complete. One reason could be during the pouring process the velocity of the pour could have been too slow. Another is the Vertical iteration was designed to be held together with nut and bolt, but the proper bolt length could not be found in time and had to resort to adhering the molds, which were not able to cure properly before casting operations.

Throughout the life of the project, requirements for a successful cast was familiarized. With the collaboration of experts from ExOne, the mold iterations evolved to a final mold which is almost unrecognizable form initial concepts. Knowledge in mold design was gained, and the casting properties of aluminum A356 was analyzed with similarities in microstructures and mechanical properties compared to alternate casting methods of the same alloy. The effect that 3d printed sand molds using binder jetting are making in industry is truly groundbreaking. Despite the casting attempts being unfulfilled completely, there was pouring practice and future work that could be implemented to guarantee successful casts.

Recommendations

Several steps can be taken to ensure that the mold is filled with the molten aluminum. The first would be to modify the rigging and gating systems of the molds so that the metal flows to several locations on the cast rather than just one. Second, prioritizing smaller features by implementing larger risers and vents so that enough material is available to counter shrinkage that occurs during solidification. Lastly, heating casting molds is a widespread practice which decreases the rate of solidification due to a lower temperature difference between the mold and the molten metal. Heating the sand molds may slow down solidification enough to ensure ample time for the metal to reach all features of the molds.

References

A356.0 Aluminum vs. A357.0 Aluminum: MakeItFrom.com. (n.d.). Retrieved July 1, 2024, from https://www.makeitfrom.com/compare/A356.0-SG70B-A13560-Cast-Aluminum/A357.0-A357.0-T61-A13570-Cast-Aluminum

Aluminum A356.0-T6, Sand Cast. (n.d.). Retrieved July 1, 2024, from https://www.matweb.com/search/datasheet.aspx?MatGUID=d524d6bf305c4ce99414cabd1c7ed070

Draft Angle—An overview | ScienceDirect Topics. (n.d.). Retrieved July 1, 2024, from https://www.sciencedirect.com/topics/engineering/draft-angle

Jiang, W., Chen, X., Wang, B., Fan, Z., & Wu, H. (2015). Effects of vibration frequency on microstructure, mechanical properties, and fracture behavior of A356 aluminum alloy obtained by expendable pattern shell casting. *The International Journal of Advanced Manufacturing Technology*, *83*. https://doi.org/10.1007/s00170-015-7586-0 liu, feng. (2009, January 23). *Optimized Design of Gating/Riser System in Casting Based on CAD and Simulation Technology*. Worcester Polytechnic Institute.

Nabil, S. T., Arrieta, E., Benedict, M., Wicker, R., & Medina, F. (2022). *Effect of Thermal Aging in the Fatigue Life of Hot Isostatic Pressed AlSi10Mg Fabricated by Laser Powder Bed Fusion*. https://doi.org/10.26153/tsw/44562

Saeidpour, M., Svenningsson, R., Gotthardsson, U., & Farre, S. (2022). Thermal Properties of 3D-Printed Sand Molds. *International Journal of Metalcasting*, *16*(1), 252–258. https://doi.org/10.1007/s40962-021-00583-x

Shabestari, S. G., & Shahri, F. (2004). Influence of modification, solidification conditions and heat treatment on the microstructure and mechanical properties of A356 aluminum alloy. *Journal of Materials Science*, *39*, 2023–2032. https://doi.org/10.1023/B:JMSC.0000017764.20609.0d

Tan, C., Shen, X., Ramesh, S., Kolahchi, R., Hajmohammad, M. H., & Rajak, D. (2022). Creep Behavior of A356 Aluminum Alloy Reinforced with Multi-Walled Carbon Nanotubes by Stir Casting. *Materials*, *15*, 8959. https://doi.org/10.3390/ma15248959

Aluminum A356.0-T6, Sand Cast. (n.d.). Retrieved July 1, 2024, from

https://www.matweb.com/search/datasheet.aspx?MatGUID=d524d6bf305c4ce99414cabd1c7ed070

Sama, S. R., & Manogharan, G. P. (n.d.). *Sand Casting Design Rules*.

Saeidpour, M., Svenningsson, R., Gotthardsson, U. *et al.* Thermal Properties of 3D-Printed Sand Molds. *Inter Metalcast* **16,** 252–258 (2022). https://doi.org/10.1007/s40962-021-00583-x

Appendix 1

	Title	Abstract	Citation

1	3D Printing Technology Dramatically Improves Manufacturing of Impellers	Kimura Foundry America President Dr. Yoya Fukuda has been with the Kimura Group for 25 years and leads the first international expansion for the company. He emphasizes a clear mission to utilize binder jetting to deliver quality to customers and helped develop a patented method of using ceramic sand in that eliminates cracks, veins, and burrs, even on steel and iron castings, and without the use of adhesives. Within the factory, the company has built a high-efficiency system for recycling and reusing the material, enabling them to deliver high quality at lower costs, while also establishing a sustainable manufacturing	Xylem Water Sol.
2	Application of sand 3D printing for stainless steel castings	30 printing for sand mold is drastically improved in recent years. Quickly prepared without wooden pattern. Making complex shape is possible. Especially printing furan resin process is gathering	Dr. Yoya Fukuda Kimura Foundry ExOne
3	Global Foundry Group Grows Business with Sand 3D Printing Innovation	By using the 3D printer from ExOne, Xylem was able to significantly simplify the manu facturing process for one of its key products: impeller cores. Since the new technology was introduced, the sand cores needed for casting water pump impellers have no longer been produced from four parts in a core shooting process — but from a single part in the 3D printer. "Our goal was to speed up production," commented Andersson. "Using the traditional method, it took seven days to manufacture impeller cores; with the 3D printer we can now do it within 48 hours."	Dr. Yoya Fukuda Kimura Foundry ExOne
4	Optimized Design of Gating/Riser System in Casting Based on CAD and Simulation Technology	Casting as a manufacturing process to make complex shapes of metal materials in mass production may experience many different defects such as porosity and incomplete filling. How to improve the casting quality becomes important. Gating/riser system design is critical to improving casting quality. The objective of the research presented in this thesis is to optimize gating/riser systems based on CAD and simulation technology with the goal of improving casting quality such as reducing incomplete filling area, decreasing large porosity and increasing yield.	Chapter 1 (woi.edu)

	Title	Abstract	Citation

5	Sand Casting Design Rules	Sand casting is the most popular casting process employed in industrybecause of its great geometric freedom capability and for its cost effectiveness. In this article, we provide design rules for optimal sand casting performance."	Santosh Reddy Sama, Guha P Manogharan Penn State University
6	Numerical Simulation of latent Heat of Solidification for Low Pressure Casting of Aluminum Alloy Wheels	problems existing in the mathematical model of temperature change in the low-pressure casting solidification process of aluminum alloy wheel hub, there is a big gap between the simulation and the actual temperature change, which affects the research on the solidification defects of the wheel hub. In order to study the solidification behavior of aluminum alloy hub In low-pressure casting process, the mathematical model describing the temperature change in the process of casting solidification is established by using different solidification latent heat methods. through finite element simulation and experiment, the temperature change in the process of aluminum alloy (A356) solidification is obtained to compare the difference between the temperature change	D01:10.3390/met10081024
7	FUNDAMENTAL STUDY ON 3D SAND PRINTED MOLDS: METAL FLOW THERMAL PROPERTIES	Fueled by the growing popularity of 3D sand printing (3DSP) molds for metal casting, this thesis took-on two research opportunities for the modeling and characterization of these materials. The first proposed a novel experimental method using succinonitrile (SCN) for modeling casting flows. Understanding the metal flow in sand-molds is critical to eliminate casting defects due to turbulent filling. While numerical methods have been applied to simulate this phenomenon, harsh foundry environments and expensive x-ray equipment have limited the experimentation to accurately visualize metal flow in sand molds. This thesis used flow simulation and experiments using both water and SCN to	Casey Bate Penn State University

		identify the critical dimensionless numbers to perform accurate metal flow	
8	Thermal Properties of 3D-Printed Sand Molds	gradient in a sand mold during casting aluminum using a commercial simulation software. The simulated results have been compared with laboratory-measured results and simulated results using the software's database for conventional mold making. Our results show that available database for sand thermal properties cannot explain the thermal gradient in 3DPS molds and this manufacturing process affects the thermal properties of the mold compared to traditional mold making. it is necessary to collect data for a variety of 3D-printed sand molds to ensure accurate modeling cimulatinn	Saeidpour, M., Svenningsson, R., Gotthardsson, U. *et o:*
9	Property Table for Aluminum A356.0•6	Property Table for Aluminum A356.0•6	Matweb