ADDITIVE MANUFACTURING ASSISTED
CASTING METHODS FOR ALUMINUM

By

JEFFERSON HARRISON

Bachelor of Science in Mechanical Engineering

Oklahoma State University

Stillwater, OK

2017

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2022

ADDITIVE MANUFACTURING ASSISTED

CASTING METHODS FOR ALUMINUM

Thesis Approved:

Dr. Ranji Vaidyanathan

Thesis Adviser

Dr. Jacob Bair

Dr. Joe Conner

ACKNOWLEDGEMENTS

Special thanks are extended to Michael Costa and Mikael Garcia for their support and help in performing this research. This extended to exceptional work and time for getting procedures accomplished that allowed the completion of this paper.

Thank you, to Alton Livingstone of Advanced Ceramics Manufacturing and James Rorls of CadBlu, for the indispensable knowledge of operating and troubleshooting the Additive manufacturing equipment.

Thanks to John Gage of the Oklahoma State University Design and Manufacturing lab for help and performance of the casting operations.

This work was funded by Tinker Air Force Base in Oklahoma City, Oklahoma.

Name: JEFFERSON HARRISON

Date of Degree: DECEMBER, 2022

Title of Study: ADDITIVE MANUFACTURING ASSISTED CASTING METHODS FOR ALUMINUM

Major Field: MATERIALS SCIENCE AND ENGINEERING

Abstract: Through the rise in additive manufacturing increased efforts are being made to utilize these processes in traditional manufacturing. This allows for the increased complexity and expedited processing which would otherwise be unavailable to traditional casting operations. The objective of this paper is to compare multiple methods of additive manufacturing assistance to determine the best procedures for producing a complex part that would otherwise be unattainable through traditional casting. Two methods were studied binder jet assistance of sand casting, and poly jet assistance of investment casting. The study and comparison consisted of dimensional comparison to determine the adequacy and capability of the proposed methods, while also discussing the drawback and disadvantages experienced during production of the casting molds. The results indicate that significant improvements of time can be managed, but careful consideration to mold design must be maintained to ensure best production capability.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

Traditional casting methods are vast and have been used for thousands of years. In recent years though more metallic alloys have been developed and with increased design requirements, previous methods need to be modified to allow for continued casting operations. One of these modifications that has been sought is the additional complexity of design requirements [1][2]. These complexities have caused complications for traditional casting methods and therefore the use of additive assisted casting procedures have grown in popularity throughout the foundry industry. Additive manufacturing is a layer-by-layer process of creating 3-dimensional shapes [3]. This is commonly referred to as 3D Printing, and was originally developed as rapid prototyping technique for use in design validation. As the growth of additive manufacturing has occurred so have the capabilities. Multiple processes have been determined and researched for the sole purpose of assisting traditional manufacturing techniques. The two that will be discussed throughout this paper are polyjet method of wax pattern creation for Investment Casting, and Binder jet mold generation for sand casting. These two methods have been proposed as possible alternatives to the traditional casting methods for the shown bearing housing, figure 1. The part features and geometry create complications for both of these traditional methods, such as the fins, shown figure 1b. In order to better understand the

B complications and the requirements for additive manufacturing assistance the traditional methods must be discussed.

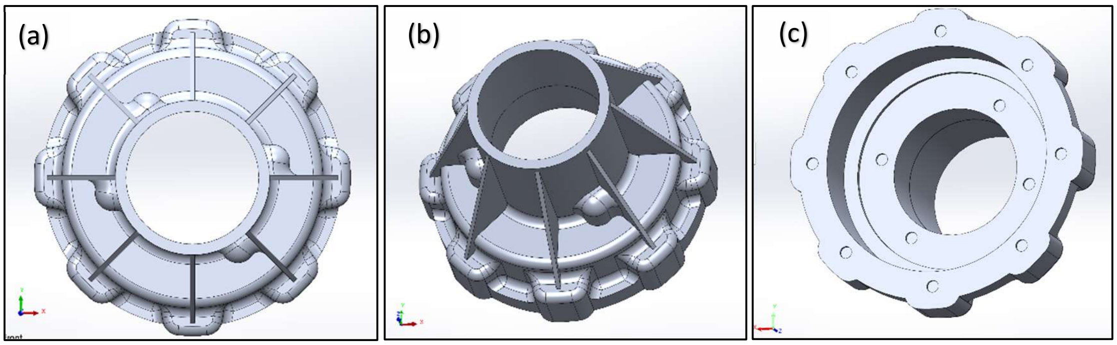


Figure 1. Bearing Housing Model: (a) Top View; (b) Orthogonal Features Display; (c) Bottom Features Display

Sand casting requires the creation of a pattern part, this part must have drafted features and account for shrinkage factors [5]. This pattern generation will be done by traditional manufacturing procedures such as Computer Numerical Controlled (CNC) Milling, with this manufacturing model generation, job routing, and then machining must be performed. Any additional complexities will impact the schedule and difficulty of operations and in some cases make impossible geometry to achieve through CNC Machining. Upon the pattern being completed the casting procedure can begin. The use of green sand is common and refers to the sand that will be utilized to create the mold, this sand will be packed into the drag (bottom) box, and the pattern will be placed into the sand. At this point the cope (top) box will be installed and then sand will continue to be packed around the pattern [4]. Once the sand is sufficiently packed the cope and drag will be separated to allow for pattern removal. This is where the drafted features come into effect, if not enough draft occurs the sand will be disrupted upon removal. With pattern removed the gating system, vent holes, and sprue must be created in the sand, Figure 2. These will allow the flow of metal into the pattern and evacuation of air. The mold is then ready for casting operations.

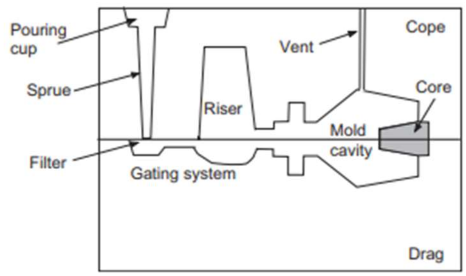


Figure 2. Schematic diagram of a sand-casting mold, showing the upper half(cope), lower half (drag), and core in place. [4]

Investment casting is commonly referred to as lost wax casting as the pattern is traditionally made from wax and will be removed and subsequently lost throughout operations. For investment casting a pattern must also be created, however depending on production size will determine method of manufacture. If large production is necessary the use of CNC machining may be utilized to create a high precision mold that the wax can be injected into for pattern creation [1]. If the production is small though machining or modeling of the pattern by other means can be used. Once the wax pattern is available the pattern has a ceramic shell applied to it by subsequent operations of slurry and ceramic particles. After desired thickness is reached the wax is removed and firing occurs to harden the ceramic. At this point the mold is ready for casting operations. A very detailed schematic of investment casting operations was produced by Mukhtarkhanov in figure 3 [1].

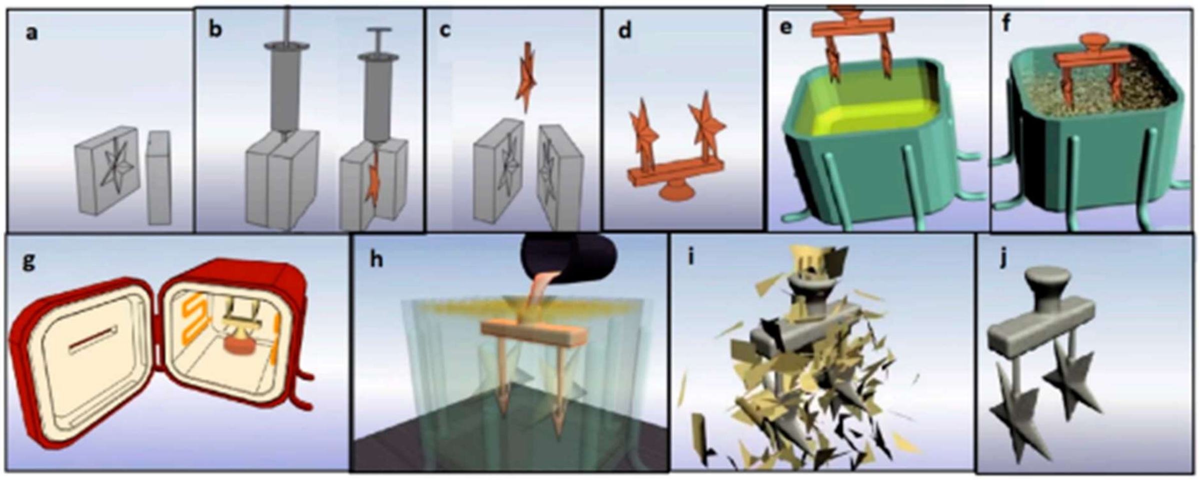


Figure 3. Schematic Illustration of investment casting (IC) process: (a) Metal mold prepared for wax injection; (b) Wax pattern making by injection; (c) Wax ejected from the mold; (d) Wax patterns assembled in a tree; (e) Coating with ceramic slurry; (f) Stucco Coating; (g) Dewaxing through heating; (h) Metal Pouring; (i) Destroying ceramic shell; (j) Casted part ready to be cut off from the assembly. [1]

With the use of traditional manufacturing requirements for the initial stages of both these casting operations limitations in complexity and geometry are reached. Which is the reason for the research into additive assistance, by utilizing additive manufacturing these complexities are negated by losing traditional design restrictions. This does not change however that certain casting operations are preferred or more desirable for certain components. Sand casting delivers high quality components that require more substantial post processing, but can produce larger components [2]. Investment casting is not the opposite, but is known for producing better surface finish and has some size restrictions due to the ceramic shell application [1]. The intent of this research is to determine the optimal manufacturing method for the bearing housing. The primary complications of this component that lend it to this study is the complexity of features, features detrimentally affected by draft, and the low production scale desired.

CHAPTER II

REVIEW OF LITERATURE

Additive manufacturing has allowed for the expedition of traditional manufacturing since the onset, when it was more widely referred to as Rapid Prototyping. The next steps away from rapid prototyping though has been under constant scrutiny from industry. In an effort to bridge the gap the use of Additive manufacturing in secondary operations has been attempted. Among these secondary processes are part generation for investment casting or mold generation for sand casting. Part generation using additive manufacturing is a very simple and effective method. Many types of additive manufacturing can be utilized for the part generation [1]. The basis of investment casting remains identical, but removes the need for complicated metal mold to create the wax pattern. Similar results can be seen for the sand mold generation by additive manufacturing. Through the use of Binder jet technology, the sand mold can be generated without need for initial pattern utilized in making the Cope and Drag and removal of drafted features requiring machining [2]. The simplification of casting procedures can in turn be maximized by increasing capability of productions parts. Through traditional manufacturing methods complexities of parts must be accounted for in the design. In additive manufacturing these issues become secondary as the technology is able to create intricate features and puts reliance upon the casting analysis to ensure feeding and solidification occurs satisfactorily [5]. This analysis of solidification is a primary component to all casting procedures, but with increased complexity more information must be acquired to properly design molds.

The parameters not affected by the additive manufacturing process must also be discussed. These parameters stem largely from behavior of molten metal and the interaction with the mold. This interaction is not affected by the additive manufacturing starting points, but has large influences upon the results of casting operations. The fluidity of metals is influenced by many variables with largest emphasis on the superheat [6][7]. While superheat is of large importance other variables that need to be acknowledged are fluid flow and mold coats [6]. All of these factors lead into various points of discussion. Santhi, discussed the shrinkage of aluminum and studied the effect of superheat and mold coats on shrinkage [8]. The combination of fluidity and then shrinkage of casting materials is in turn where the use of simulations to determine optimal parameters. An important aspect of these simulations is the alloy, the basics of casting transcend alloys. Yet, any alloy will have its own requirements outside of just melting temperature. This study utilized solely Aluminum alloys and as can be seen from Kearney [9], aluminum has variety of casting properties dependent on the alloying elements and amount. This discussion of aluminum in relation to general casting is critical for overall development. This study however highlights the capability of additive manufacturing and must showcase the intricacies of additive manufacturing that will affect the casting procedures. As two different casting procedures are discussed then an individual review of literature is necessary.

Additive Manufacturing – Related to Sand Casting

Binder Jet sand casting as discussed by Sivarupan, is a growing area [1]. This does not change that the process needs to be much more thoroughly researched. The individual effect of both the sand and binder can be shown to increase or decrease the capability of the sand molds [10][11][16]. In Khandelwal's study of binder composition it can be shown that with varying ratio of binder the shrinkage, hardness, and weight are affected. This shrinkage and weight are further validated in a study by Mitra [12]. Mitra also delved into the effect of time in relation to sand mold strength. The effect of time enters into a larger process parameter discussion as to the control of sand mold creation. The process parameters are the primary point of discussion for a majority of additively manufactured sand molds [12][13][14][15]. These studies go into great depth about a variety of process parameters. Ageing or curing occurs to all sand molds, this is simply the process of letting the binder solidify [12][14]. Mitra displays the prolonged curing is detrimental to the three-point bending strength and may cause degradation of the mold's capabilities. Khandewal though shows that mechanical properties are increased with time. The primary difference here is the effect of curing temperature, Mitra utilized elevated temperature curing whereas Khandewal performed room temperature curing. The effect of temperature is on the evaporation of binder from the sand. This not only effects the mechanical properties, but the permeability of the sand molds. Permeability is the capability for gases to escape through the sand away from the cavity due to the influx of aluminum. The permeability is mentioned in most articles involving additive manufacturing of sand molds. The optimization study performed by Kumaravadivel explains the reasoning for this as it concludes that permeability is the single largest factor affecting casting defects [16]. Throughout the use of additive manufacturing one prominent point of discussion falls to the build direction. This continues into the study of sand-casting molds by Coniglio and Sivarupan, who discussed multiple process parameters that will affect the permeability and the three-point bending strength [13][15]. The primary parameter of importance is the build direction which shows a higher permeability when positioned in the X direction, results displayed in figure 4. Which can be taken a step farther to distinguish a dependency on the recoater speed. The three-point bending in the study was noted to decrease with increased recoater speed, yet showed little variation based on build direction. These studies also bring about the initial look into Sand-Binder Ratio as the plots utilize density to normalize values [13]. Sand binder ratio is where the biggest variations in properties will be altered, and a substantial amount of research has been undergone and the studies must acknowledge this dependence [8-14].

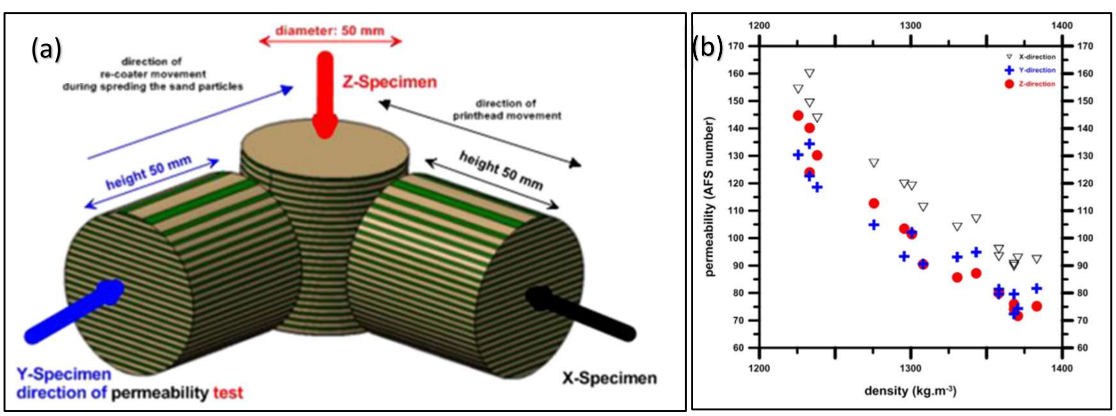


Figure 4. Permeability testing performed by Coniglio et al: (a) Schematic of the direction of permeability test on the X, Y, and Z cylindrical specimens; (b) Relationship between density and permeability for X-, Y-, and Z-Oriented specimens. [13]

This sand binder ratio has implications to alter every stage of the mold generation. The shrinkage of sand will impart additional restrictions on the mold creation and scaling of the model file. This shrinkage of sand cores was discussed by Khandewal. The study identified that increased binder content by percentage would drastically increase the shrinkage experienced [10]. This study also identified that increased hardness and weight loss from the increased binder content. This was further verified by studies from Martinez, who investigated the variation of binder content throughout the mold to increase the mechanical properties while maintain permeability [17]. This maintaining of permeability is tied to the pore size and has been studied by Sundaram, which signifies that as Pore size increases the permeability increases. However, other factors will affect the pore and permeability such as the curing [12]. Mitra, showcases as curing time increases the mass loss increases, which inherently would indicate an increase in the porosity. When the data though is displayed to showcase permeability in relation to mass loss the permeability decreases as mass decreases, see Figure 5. This is representative of the shortening resin bridges which in turn collapse pores and restrict the gaseous movement. Due to the large amount of first and second order interactions that are shown in the additive manufacturing of sand molds a study was performed to model and develop relations of permeability and strength [19].

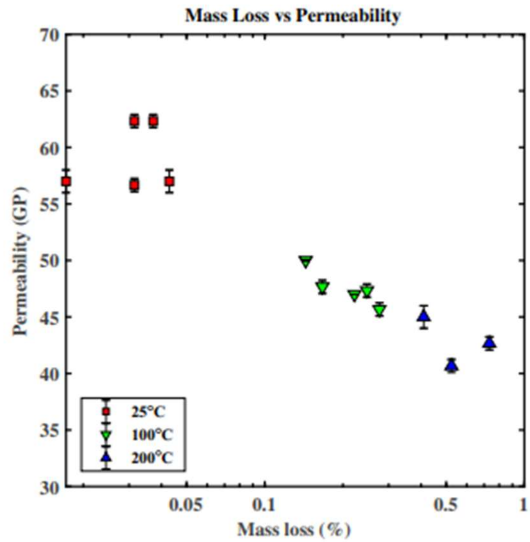


Figure 5. Permeability vs. Mass loss for three curing temperatures, [12]

Mckenna, through the use of Design of Experiments was able to find models using the functions of temperature and time to find optimal criteria for permeability and compressive strength. The factors chosen are from the post processing curing and therefore must be taken into account as the chemical composition of resin dependent. The results indicated two different temperature and time combinations for the respective parameters. Another study into the modeling in an effort to determine casting defects was performed by Kumaravadivel [20]. The research indicated the ability to model casting defects by taking into account, moisture content, permeability, volatile content, and mold pressure. These parameters should be determinable from simple analysis of the individual molds and therefore allows for greater reduction of the casting defects. These studies provide a baseline and showcases the use of Design of experiments to develop models and optimize the procedures used by additive manufacturing.

Additive Manufacturing – Related to Investment Casting

Primary instances of additive manufacturing being used to benefit Investment casting is in the creation of molds. Traditional methods require metallic molds that use high precision manufacturing to make wax patterns. This in turn creates the possibility for expediting either the mold generation or the wax pattern generation [1][21]. Many methods and materials are available for use with additive manufacturing and thus depending on production size and complexity is the key determination as to which method of additive manufacturing is preferred. In the feature written by Rooks, it was discussed that a majority of industrial partners using additive manufacturing assistance are not specialized on certain processes [22]. Instead, they gather the design of desired parts and then choose the correct machinery and type of Additive manufacturing based on the specific desire of the customer. This approach allows for the more efficient use of additive manufacturing and a reduction in the problems of conforming a part to an ill-suited procedure. These procedures also result in reduced processing time and increased collaboration between design teams and the finalized part [23]. According to the study performed by Wu, through the use of additive manufacturing the process saved 145 days compared to traditional manufacturing. While speed of production is incredibly important, it is only beneficial based on volume required. A guaranteed benefit though of additive manufacturing regardless of production needs is part complexity. However, this does not negate the fact that investment casting procedures become difficult and far more intensive than other casting operations beyond a certain scope. This scope is primarily met due procedures that are involved with the creation of ceramic shells and the risk of ceramic failure [1][24][25].

The focus of this research has been on the use of additive manufacturing to directly create the wax patterns necessary for investment casting. As such the key starting point is a discussion of the wax, the wax must be dimensionally stable, able to be handled, low shrinkage, and low melting point [26]. As wax is classified as a thermoplastic material capable of multiple melt and solidifications the key parameter to affect all these parameters is the temperature. If temperature at any stage of processing reaches a critical point the wax will begin to show detrimental effects to the casting procedure. Thus, careful considerations must be taken for preparing the wax for ceramic slurry as to not raise the temperature or create any additional features. These additional features will in turn result in loss of dimensional accuracy of the part and a compilation of errors can occur. In Yarlagadda's study of the accuracy of wax patterns it was noted the types of dimensions that need to be monitored, namely the constrained versus unconstrained dimensions [27]. This dimensional discussion allows for the correlation between manufacture of the wax patterns, post processing effects, and ceramic dimensions seen. A large parameter that affects the wax properties and accuracy is the method of manufacturing. While in this study they utilized molds to create the wax pattern the information is also pertinent to wax pattern generated by additive manufacturing in maintaining temperature and process parameters to preserve the wax patterns.

As the wax patterns are finalized information in regards to the ceramic shell is necessary to be implemented to adequately produce the investment parts. The ceramic coating requires a stepwise process of applying slurry and silica sand to create the shell. Due to the nature of this process the most important parameter is the shell thickness, as studied by Yao [24]. In this study he displayed that with adequate thickness no cracking was seen to occur even if thermal expansion of the pattern occurred, results displayed in figure 6. However, the additional thickness creates issues in the efficiency of components produced. Parts will lose their value with each additional coat creating excess material waste. In this manner it is better to find optimal thickness to ensure the ceramic will experience no cracking during the wax removal stage. The primary two methods to increase ceramic shell while decreasing the thickness come from very different processes. Yao goes on to discuss by use of Finite element Analysis that if the pattern is capable of geometric configuration to reduce the thermal expansion it can experience then the ceramic requires less strength [24]. This can be done by cross hatching the interior of the pattern, for typical wax patterns this may be a difficult approach to accomplish, but would be a very beneficial point of research, figure 7. The other method for increasing ceramic strength is additional reinforcement. This can be accomplished through a variety of ways and materials. Lu discussed the benefits and differences between the use of Aluminum oxide and Zirconium oxide fibers to reinforce the ceramic shell [25]. These materials required in depth processing and understanding of the interactions experienced between the fibers and ceramic shell. It was noted that both materials did increase the mechanical properties of the shell, but some shrinkage was noted based on the weight percent added to the ceramic. This however, provides a realistic approach at how to strengthen ceramic shells without the use of additional software manipulation to model internal geometries. Upon the ceramic shell being prepared the final processing of the molds for pouring follows the same principles of investment casting.

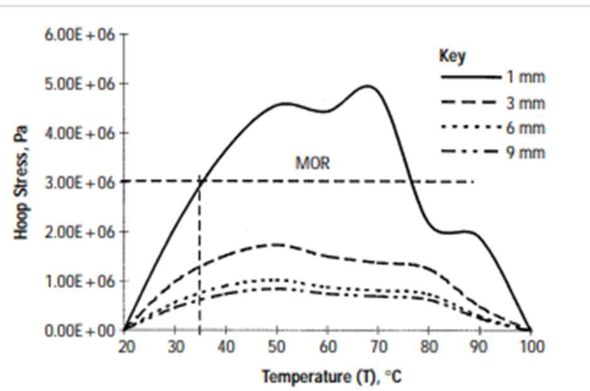


Figure 6. Induced maximum hoop stress as a function of temperature for different shell thickness [24]

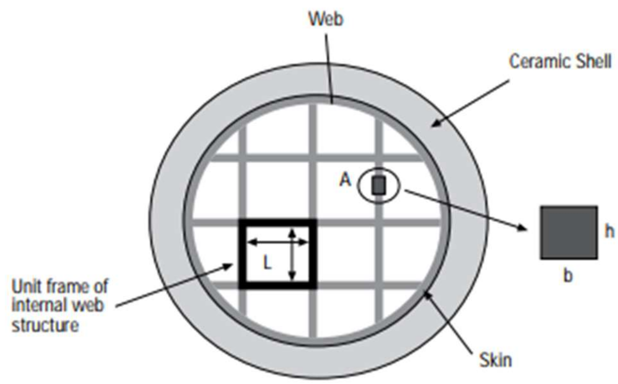


Figure 7. Internally webbed pattern with ceramic shell [24]

CHAPTER III

MACHINE SETUP AND MAINTENANCE

With the analysis of two different additive manufacturing approaches the use of multiple machines was required. The Projet MJP 2500 IC developed and manufactured by 3D Systems, utilizes the principles behind polyjet printing without the need for Ultra violet curing. This allows for precise and very detailed wax patterns being produced with substantial speed. This machine was utilized to showcase the capability of Investment casting with Additive manufacturing assistance. The Additive machines that would be used for the comparison with sand mold generation, are the ZCorp 310 and ZCorp810. These machines utilized sand and binder of various combinations to remove the need for traditional pattern creation and packing from sand casting operations. The removal of this step also allowed for more research into unattainable geometry that may increase casting capability. The use and operation of these machines was crucial to the study and determination of the preferred additive assistance.

Projet MJP 2500 IC – Wax Patterns

The installation of Projet MJP 2500 IC was very quick and required storage and operation limits that can be met by general industrial facilities. This includes adequate ventilation to ensure overheating and particulates do not cause hazards. The electrical requirements while very simple did recommend the use with an Uninterruptible Power Source (UPS). The UPS was manufactured by CyberPower model PR3000LCD, which required a three-phase outlet be installed. The UPS will keep from any damage to the printer from unanticipated shutdown. The ten-hour battery life allows for sufficient time to correctly shut down the Projet Printer. The other requirements for set up and use of the Projet printer is the appropriate software licensed by 3D Systems, 3D Sprint Basic. This software allows model creation, generation and importing of .stl files, and the creation of job files without the requirement of any additional software. This is unique in that additive manufacturing printers typically require multiple software's for each individual component of the design and manufacturing process.

Along with installation the continued use of the machine is relevant to the comparison and as such requires explanation of the typical maintenance, issues, and resolutions encountered. The Projet printer utilizes a planarizer to ensure the surface of each layer is perfectly flat and capable of additional layers being applied. If any wax material builds up the residual thickness will in turn create catastrophic part failure as the layers will be unable to bond. This planarizer must be periodically checked and the planarizer wiper blade that cleans and ensures no residue buildup must be maintained. The material removed by the wiper blade is intended to travel into the planarizer ducts. These ducts will then direct the flow of wax into the waste bag. If the ducts are not routinely cleaned then wax buildup will occur and over flow into the job box, thus creating additional issues with movement of the print engine. The final routine maintenance is the cleaning of the print engine optical sensor. This sensor is used to ensure the print engine is homed properly and as the print engine moves some particulate residue is seen throughout the job box the sensor may become obstructed. The cleaning of all these items is simple and does not require more than standard materials. The use of Isopropyl Alcohol 95%+ and lint free cloth is sufficient to remove any residue that could have accumulated. This cleaning needs to occur at a frequency to ensure no hardening of wax, recommended to be performed weekly or more if use is extensive.

The machine operated efficiently and effectively for a substantial amount of time. However, when the frequency of use dropped beyond a minimum of one job a week the jets began to show signs of closure. This was evidenced by cracks in the wax pattern created and a stripe along the witness coupon showcasing the approximate jets being obstructed, figure 8. The Projet printer comes with the capability to test the individual jets for obstructions, upon completing the test. It was determined approximately an eighth of an inch was affected and needed further maintenance to correct, figure 9a. A recover jets cycle was run, in which material is forcefully pushed through each jet to remove any hardened residue and clean the lines. After recovering jets, a maintenance head cycle is required to clean the print head and ensure no splatter of wax remains on the print head. Upon completion of these steps testing of the jets occurs. This continues until the jets are corrected or no appreciable corrections are being noted, figure 9b. If no corrections are seen after these operations, then additional maintenance may be required by a technical specialist. The printer can still be utilized to make sufficient patterns, but require a knowledge of the job box and the ability to utilize areas unaffected by any obstructed jets.

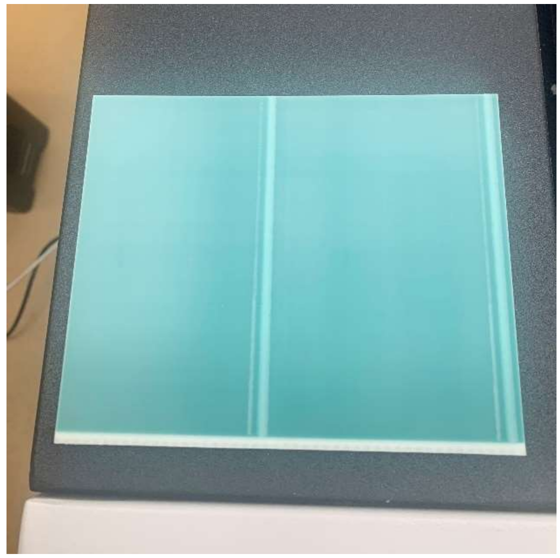


Figure 8. Witness Coupon showcasing discrepancies during part manufacture

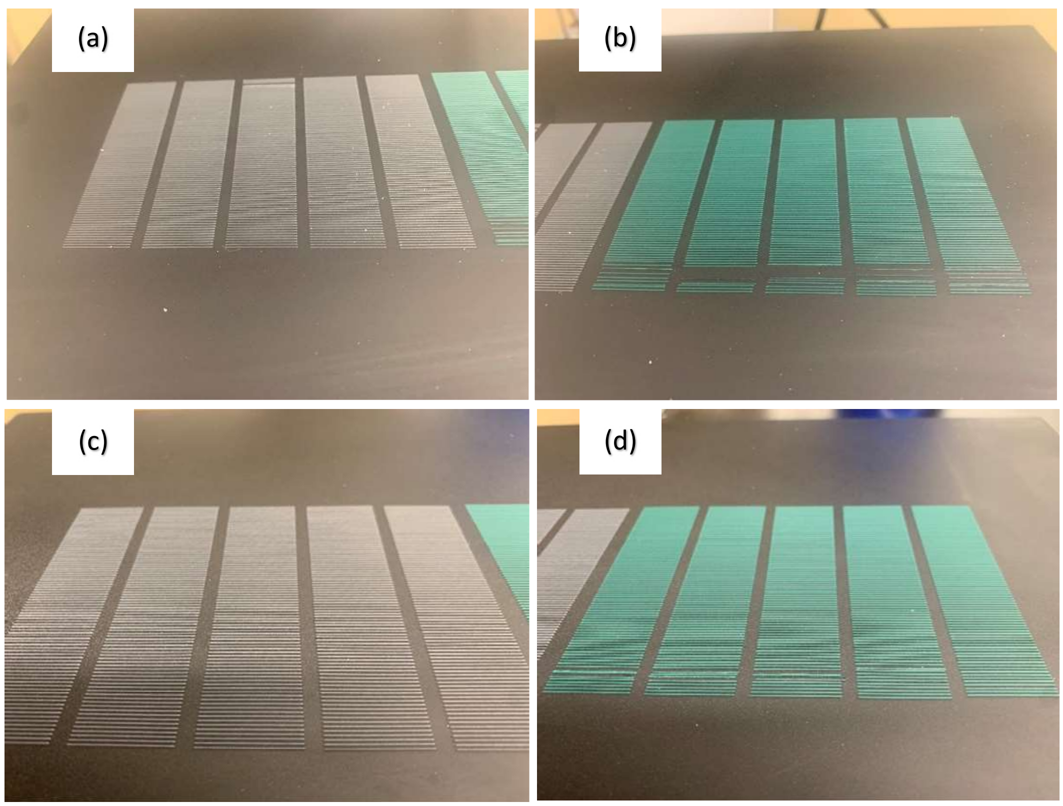


Figure 9. Printer Jet Correction: (a) Initial Support jet; (b) Initial Wax jets; (c) Final Support jet test; Final Wax jet Test

ZCorp 310 & 810 – Sand Mold

The ZCorp 310 and 810 printers have some very significant differences that result in variations in the installation requirements. The ZCorp 310 has a small footprint and therefore does not require much outside of what is readily available in industrial facilities. The ZCorp 810, though requires more thought for location of installation. This results from the combined length of the ZF8 Powder feeder, when correctly installed the overall machine takes on a footprint of 7'6" long, 6'6" tall, and 3'9" wide. These dimensions are no bigger than other machinery utilized, though for access to the job box the lid must be capable of fully opening. With the lid open to access the job box the height changes to 9'6", as the door covers an approximate area of 4'9" long and 3'9" wide. Upon accounting or sufficient operation area and surroundings the electrical requirements are powered by standard 120 Volt outlets. The Z810 also has the additional requirement of pressurized air, this is used in the ZF8 Powder Feeder to allow vacuum capability for post processing steps.

The operating system for running the printers was, ZPrint 7.9, which was licensed by ZCorp. This software however was unable to run on newer versions of Windows and required the use of a desktop computer that operating on Windows XP. This software allowed the use of importing .stl files and positioning inside the Job Box. Along with basic positioning and tracking of the print job completion, the software would allow the modification of sand-binder ratio and options of sand or binder to be used. The machines came with and were setup to run utilizing RapidCore (Z130 powder). Some things of interest are that with the use of Windows XP the printers and computers are unable to be connected to the network and therefore require separate mode of connection. Through the use of a network hub the printers could communicate with the software. The network hub setup required the manual configuration of unique IP addresses for each printer prior to connection to the computer. Upon receipt and initial setup, the printers utilized the same IP address and therefore had issues with determining which printer was being operated. To alter the IP address the initialization code (.ini code) was reset and the chosen IP Addresses were entered. The .ini code is a text source file that allows the adjusting of key values and parameters of the printer. After the computer and printer was effectively communicating information. The Zprint software had the ability to determine if any mechanical issues had arisen during transit, but all axis had sufficient motion.

After determining the printers were in satisfactory working order the binder needed to be manufactured. The rapidcore sand already has some chemical compounds that are used to assist the binding reaction and therefore uses a simpler binder solution for normal use. The binder consisted of Deionized water (DI Water), Polyethylene Glycol (PEG), Triton X-100, and Polyvinylpyrrolidone K-30 (PVP). The use of volume ratio ensured the appropriate content regardless of the desired batch size. The standard volume was 1 gallon, which was converted into liters for ease of measurement, 3.677Liters-DI Water, 60.06mL-PEG, 17.82mL-Triton, and 38.14g-PVP Powder. Upon Measuring the chemicals are mixed for 12 hours to ensure homogeneity and adequate dispersion of PVP powder. Care had to be taken to avoid overly turbulent stirring as foam would form and affect the mixing process. The binder is then passed through a 10-micron filter to remove any contaminants from atmosphere and conglomeration of powder. As the binder has no bacterial protection new binder is recommended to be manufactured weekly, as this will stop any organism growth and contamination of the binder lines. This binder can then be installed in the printers and undergo the loading process to ensure new binder is being used. This requires filling respective Binder jugs, and then running flush cycles from the ZPrint software to pull binder through all lines and dispense the older binder into the waste jug.

The next preparation of the printers is in relation to the print heads. Both ZCorp printers make use of the HP10 printer cartridges. These are standard cartridge that have ink already inside of them, this requires the cleaning of the print cartridge and then refilling with binder. To remove the ink required a vacuum system to pull the fluid into a trap while pulling cleaning solution through the cartridge, figure 10. The cleaning solution is ZC 5, which is a diluted ethanol solution. After running the system until the fluid flow is clear the refilling of binder is done using the same system. The binder must be run for adequate time for the cleaning solution to be removed. At this point the print cartridge is primed and can be installed into the printer. When these steps are completed, the printers simply require the input of powder to be operational. The printers require two different processes of getting sand loaded into their respective feeders. The Z310 makes use of a feeder bed, this bed has the same volume as the build bed for simplicity. The process of filling requires physically filling the bed with the desired powder and once the volume of powder is filled using light force to ensure smooth packing and level top surface. This powder can then be used to fill in the build bed, the build bed will be bulk filled and then perform carving operations to get the required surface of powder. The Z810 has one key difference, due to the powder feeder. If the ZF8 has been connected to pressure, then a vacuum system can be utilized to insert the powder. Insert the vacuum hose into the desired powder and turn on the system, as the feeder fills the sensors inside indicate the level of fill that has been achieved. Once the highest sensors have been covered the vacuum will turn off and the powder is vibrated. This vibration settles the powder and will level the powder to determine if the sufficient powder level has been reached. If the maximum sensor is still covered, then the powder feeder is full. An important note to this is the powder feeder display that is available in ZPrint is only accurate to four inches. Identical to the Z310 the build bed still needs to be prepared. This requires bulk dispensing of the powder until full and then a few additional layers to ensure a proper surface. All of this is the ideal case of fully operational installation and setup of the ZCorp printers, the remainder of this section will discuss the issues and corrections that were performed in regards to the Z310 and Z810.

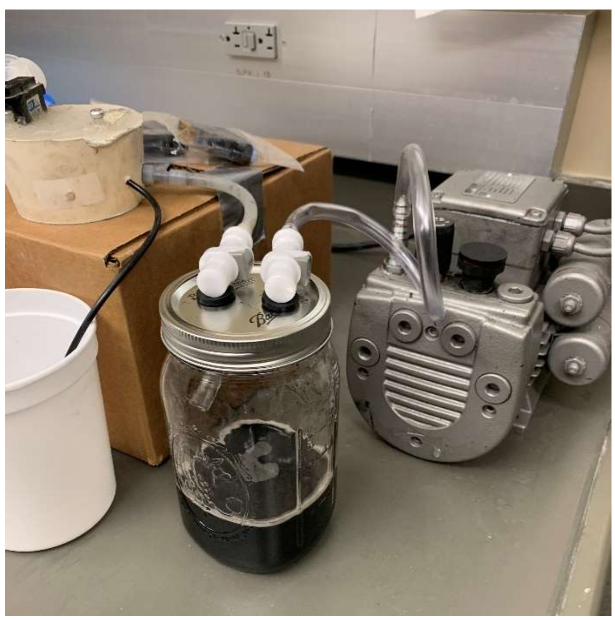


Figure 10. Vacuum system for Purging and Priming Operations

Z810

When installing the Z810 the powder feeder was found too not be fully operational. Without operations manual many attempts were undertaken to determine the primary cause of the issue. The issue was in fact to the lack of powder being dispensed. When attempting to fill the bed the flapper motor used for controlling powder dispensing was engaged, but only residual powder was dispensed. Upon closer inspection of the powder feeder, it was noted that there are two motors. The first motor moves the powder from the feeder into the drop basin, and the second one controls the flaps to place the powder into the printer. It was noted that only one motor was activating during our initial setup. The troubleshooting process required the removal of access panels to inspect the circuits and connections of the motor. Once panels were removed the motor was able to be uninstalled and independently checked, see figure 11. The method of checking was to connect the motor to a direct current power source and determine if there was any movement. Despite being unable to apply the required voltage sufficient voltage was delivered to show that the motor was capable of movement. After reinstalling the motor, the next step was to check any connections and ensure adequate voltage was present to activate the motor. All circuits were determined to be adequate and no fuses had been blown. When inspecting the mother board, it was noted that some indicator lights were not activating. This indicator was tied to the pressure being delivered into the powder feeder. Using this indicator, the air pressure was increased, once the indicator was activated the motor began to turn. This explained the solution to the issues being that the powder feeder required a minimum of 40psi for full operations.

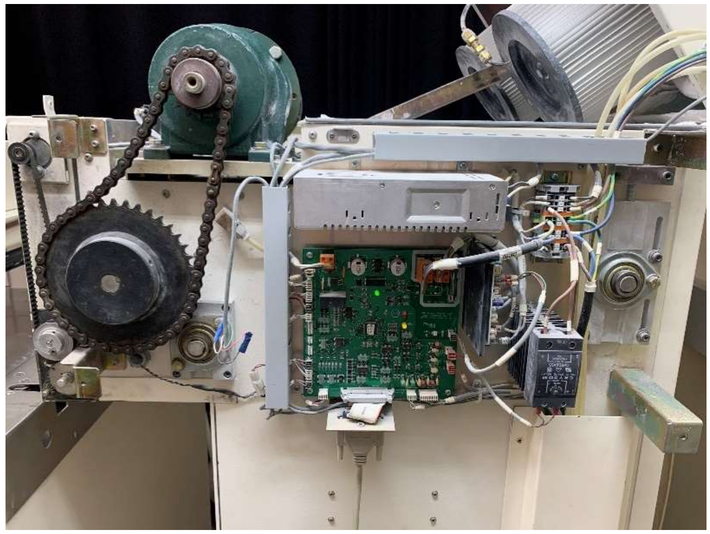


Figure 11. Access panel of ZF8 Removed during motor investigation

Once the powder feeder was able to properly move sand into the Z810 Printer, the bed filling operations were attempted. During these operations the bed did not fill evenly, nor did the bulk filling cover the entire build box. The box was filled to approximately 75 percent covered. In an attempt to remedy the lack of sufficient powder the .ini code was adjusted. The code was capable of adjusting the powder dispense ratio, the increasing of this ratio would allow for longer door opening with the desired effect being more powder pulled into the printer. This change to the .ini code had the desired effect with simple altering of the code more powder was being dispensed for use. This did not affect the layer size as that is controlled with the roller and z-axis movement of the build platform. Once the powder being dispensed was sufficient to cover the build area filling operations were continued. It was noted this time that will the filling operations were successful and complete coverage of the platform was achieved the powder was filling nonuniformly. The powder while being pulled across did not cover a corner of the platform despite having considerable overflow each layer. When this was discovered, the proposed solution was that the platform may no longer be level relative to the print gantry. This was verified but would require higher precision tools and mechanics to achieve the desired level. Until the leveling occurs the job box can be used with careful consideration as to the location of builds.

Due to the construction and the use of a nonstandard binder formulation the binder pump system was bypassed. Instead, the use of a gravity fed system which allowed flow from an alternate container that would deliver binder without need for any mechanical operations. One thing to note was that due to this system of exposing binder lines during transport to air, the binder lines were bled to ensure no air remained trapped. This was performed by creating a vacuum and inserting binder into the lines. The issue that has arose from the gravity fed system seems to stem from the height of binder jug. Due to increased height the binder develops a pressure head that actually can push binder through connections while the printer is inactive. Simple solution is to remove binder jug connection from printer unless printing is occurring. Without further study into connection leaks, cannot determine if amounts capable of affecting part quality are occurring. If the binder flows through connectors at a rate that will detrimentally affect the build, then new binder lines may be required to ensure no connection leakage.

To determine if the binder flow would be sufficient to affect the part tolerances a job was began. The job would be tensile strength and transverse shear samples that would have standard dimensions. After the printer warmed up and began leveling of powder it displayed an error stating, ROM Head 0 Failure. From the troubleshooting documentation this was likely due to poor electrical connections of the print cartridges. To correct the issue the printer cartridges were removed and cleaned with Isopropyl Alcohol. This removed any powder residue or contamination from binder. Additionally, all connections easily accessed were checked and ensure to be properly seated. After the print heads were cleaned or replaced if deemed too damaged for use, the job was reinitiated. The error continued to occur but had changed from head 0 to head 1. This change indicated that the printer cartridges being dirty was likely the cause of the initial error, but the movement indicated that other possibilities may cause this error. For a more detailed review of the circuits the access covers were removed to have complete access to the circuit boards that controlled the print cartridges. When checking the circuit board, it was noted that the pogo pins were seized and restricted motion. Due to the nature of pogo pins they are spring loaded connections that ensure adequate connections are made despite movement. As the pins were stuck, they were losing connection upon movement or no longer making connection at any stage. The solution was to remove the pogo boards and attempt to clean the pins and enable their motion. An intensive regimen of isopropyl alcohol cleaning and then lubrication with dielectrical lubricant. This process was repeated until the pins were free of contamination and able to return to normal state with no additional force. After all boards were dried, they were reinstalled into the printer. Upon installation the job was attempted during this attempt the job began as to be expected and leveled the powder. However, when the print head began movement to dispense binder another error code was displayed. This error indicated that the fire voltage in head 5 was stuck. This error code was not in the troubleshooting document and as such the attempts at correction become much less precise. Continued cleaning of the circuit cards in the print head occurred, all electrical connections into the print head were confirmed and followed to printer mother board to ensure no loose connections. At this point the possible manual setting of the fire voltage was considered. Looking into the .ini code the fire voltage was able to be adjusted by entry. The fire voltage was changed from 0 to 1 anticipating Boolean format, when the job was started now the error read that the fire voltage was changed to 0.0000. Another adjustment of fire voltage was attempted knowing that it was not a Boolean value. The value chosen was 0.0001, however when the job began the printer ignored the change and restored the 0.0000 value. At this point the .ini code was restored to the original 0 value. The final hypothesis is the voltage required to fire the print head was stuck at 0V and therefore the print head is unable to dispense any binder. A final proposed solution is to remove head 5 from the printer operations. As the printer firmware is capable of multicolor printing would indicate the ability to fire heads independent and is unnecessary for all head use. This would still allow for the use of head 0 through head 4 and not overwhelmingly decrease the capabilities of the printer.

Z310

The initial attempts of using the Z310 printer began with cleaning and preparing the binder lines. In an effort to test a hypothesis as to the capability of the Rapidcore sand to be water activated, pure water was used to fill the binder jug and perform a test print. The test print consisted of tensile strength and transverse samples. When the print was initiated, it began to level the bed and indicated properly moving along the build platform dispensing water. After ten minutes of printing an error occurred, this error read, Head 0 Temp too high. This error did not stop the job, but was followed by non-sequential movement of the print head along the build platform. Based on troubleshooting documentation likely causes were printer cartridge cleanliness or insufficient electrical connection. Cleaned the pogo pins making electrical contact with the print head and cleaned the print cartridge with isopropyl alcohol. The error was then cleared from the system and a new job was initiated. This job ran too completion indicating that the error was properly diagnosed. When the job had waited the proper curing time an attempt to remove the samples was made. The sand indicated that no cohesion had occurred, due to the use of water caused an inability to determine if fluid was not dispensed, or if the water had not been effective at bonding the powder. The solution was to prepare the binder solution and flush the system of all water. Another job was performed, at the end of this run the powder again had no signs of cohesion and thus indicated no fluid flow. Diagnostics of the fluid lines indicated no clogs in the lines. Yet, the use of pumps to draw fluid through line showed no fluid movement. Discovered that binder residue had hardened within one of the fittings that restricted flow. This is of note as the process of determining clogs meant section by section checks and this portion could not as the fitting had restriction features to cease flow when disconnected from its counterpart. After the connection was removed and a new fitting was used to correct the flow, the binder began flowing freely. This fitting was purely a quick fix and required further development and a more efficient fitting being used that required less air being bled from the system. Careful checks of the fluid lines must occur to prevent flow problems, if the binder is exposed to air for prolonged time the binder will harden and cause restrictions or clogs.

Now that the flow has been enabled and the binder can be adequately dispensed a job was initiated. This job was unable to be completed as the head temperature was exceeded. Likely this occurred from the various processes to achieve flow of binder, the head was removed, cleaned, purged, and refilled with binder. Upon reinstallation the job was reinitiated, this job was a success and the entire part was produced. The parts required one hour curing after production before handling could occur. Once the curing was completed the parts were removed from the build platform. While being removed two of the tensile samples developed cracks, two of the transverse shear samples experienced clean breaks from their weight during removal. While loose powder was being removed from the samples the two previously cracked tensile specimens broke, see figure 12a. This left two tensile and two transverse shear samples that were unbroken, yet they did not have adequate strength for being transported and tested. In an attempt to increase the strength of the parts a new batch of binder was produced with an increased PVP concentration. The standard formulation had 1% by weight of PVP and this batch had 2% by weight. Encountered flow issues again likely due to the increased PVP content and thus removed and replaced with the standard formulation. Using the standard formulation, the saturation level of the binder/sand ratio was increased. This would in turn dispense higher volume of binder to in turn create a similar effect of increase PVP. Thus, requiring a longer dry time, prior to handling. This was shown to increase the strength of the parts, but the increased fluid created greater than anticipated drying times. The increased drying times also caused more shrinkage of parts and failure occurred upon removal from the job box, figure 12b.

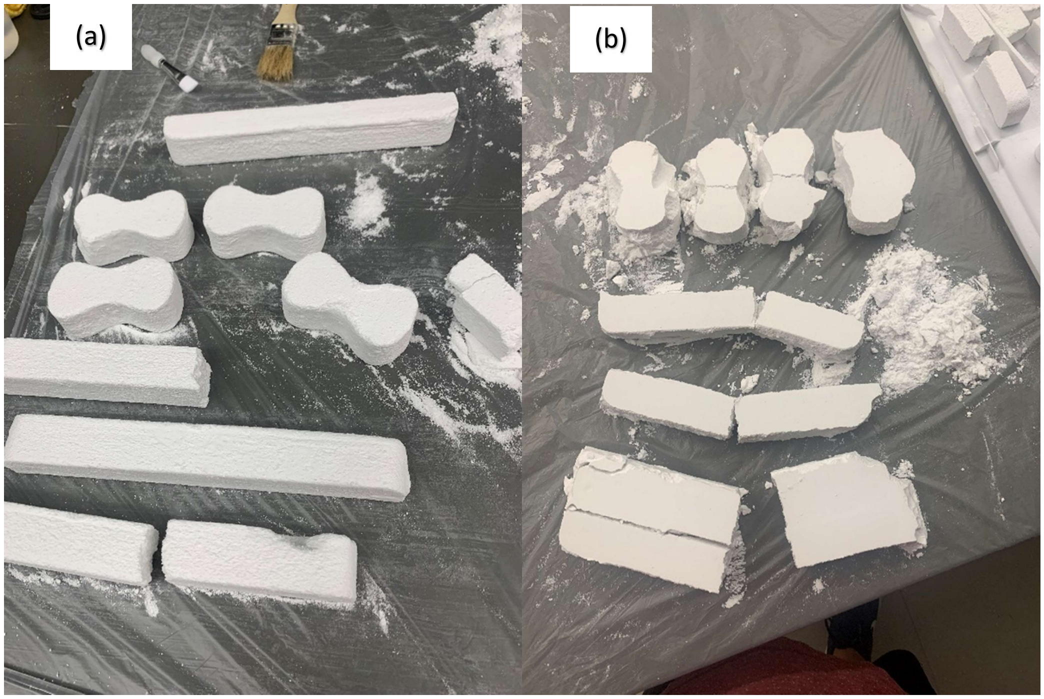


Figure 12. Tensile Strength and Transverse Shear Samples produced: (a) Traditional binder concentration, depowdered; (b) Increased Binder concentration, loose powder still adhered

These examples indicating two jobs that performed entirely and correctly. Yet, there are countless operations that resulted in general errors or incorrect printer operations. Head 0 temp too high would occur very frequently and would require the complete cleaning of the print head. This did not always correct the issue and thus further investigation occurred to ensure flow of binder. Using syringe to mimic the print head it was determined we still had flow capability and that the print heads did not seem to have any specific malfunction. Continued to see general issues with print engine not moving in the proper sequence as required to dispense binder. Frequently would move over the build platform, sit for seconds at a time and then move another layer of powder. After this occurred multiple layers in a row the job was aborted and investigation into the Y-axis motor began. The Y-axis motor is a stepper motor that controls the speed and distance of movement to properly position the head for binder dispersal. All electrical connections were checked, cleaned, and properly seated. This did not restore the proper rastering procedures. Increased lubrication of guide rails was initiated, this would decrease the force and power supplied by the motor to ensure proper print head movement. This increased the time of operation before the Y-axis failure occurred. In combination of these issues, new procedures were implemented. Lubrication of the rails, greasing of the bearing, and cleaning of the print heads was required prior to any jobs being performed. Jobs began to make it to approximately 50-60% completion prior to any motor or temperature related issues occurring. The final job attempt consisted of complete cleaning cycle, removal of all feeder powder, refilling all powder, lubrication, greasing, new print head being cleaned and primed, prior to job initiation. This job was a complete sand mold as needed for sand casting operations, figure 13; the job made it 60 layers in before failure of the Y-axis occurred. Unnoticed though was that a leak had developed. The binder began flowing freely into the printer compartment. This binder caused the need for complete cleaning of the printer compartment, including the entire job box. Once the compartment was clean and available for use again, the job was reinitiated, which prompted an error, Temp Calibration Exceeded: 0mA. This is possibly due to the excess binder that flowed into the compartment, but requires further investigation to determine corrective actions.

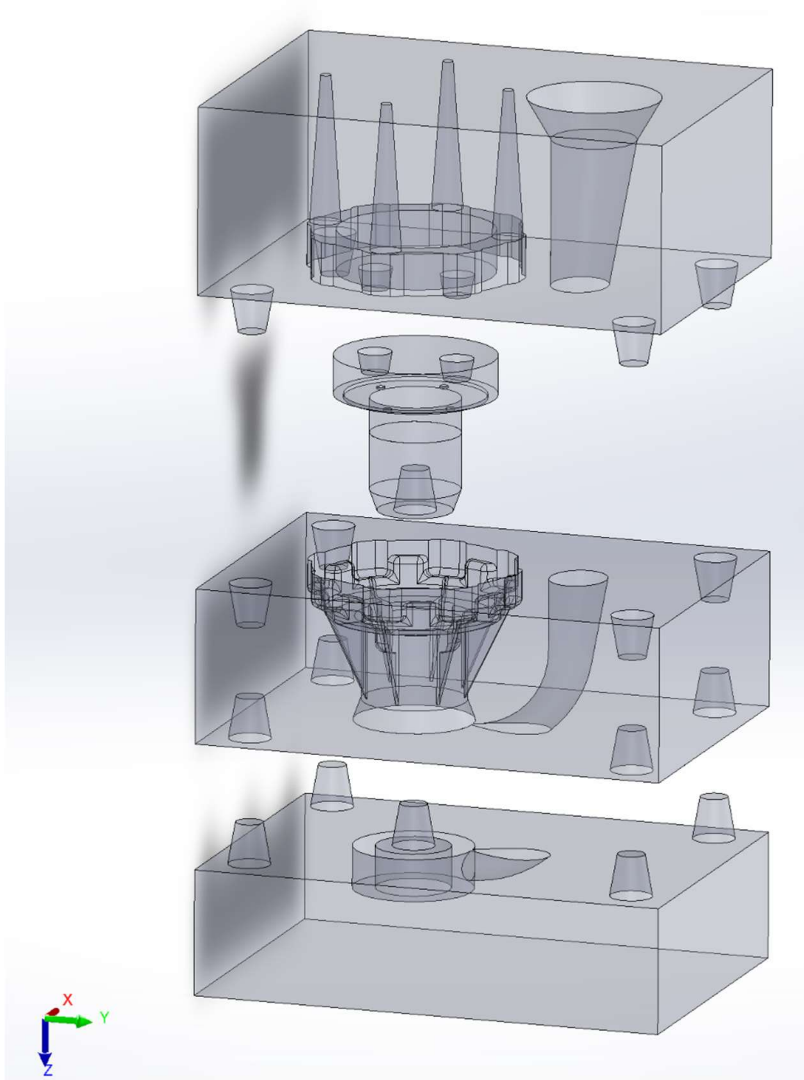


Figure 13. Sand Mold Model for attempted casting operations

An in general overview of the common errors experienced are the Y-Axis moving non-sequentially, head temperature being high, computer sleeping cause loss of connection, and packet time out occurring due to information lag. Possible corrective actions that have been hypothesized but will require further investigation are, retrofit and update of circuitry, and replacement of HP10 print cartridges with a more robust alternate.

CHAPTER IV

METHODOLOGY

Investment Casting - Projet MJP 2500 IC

Use of Projet MJP 2500 IC, allows for the creation of high tolerance wax patterns. The system boasts a dimensional accuracy of +/- 0.004inch, this study does not look into the individual dimensional accuracy and takes the values published by 3DSystems as accurate. This printer is most closely classified as poly jet and dispenses the pattern Wax, VisiJet M2 ICast, and support wax, VisiJet M2 IC SUW. The pattern wax requires cleaning to remove any of the support wax that is required for overhangs and other intricate geometries. The support wax is able to dissolved by the use of Isopropyl Alcohol, for easier removal and expedition an ultrasonic cleaner was utilized. The Ultrasonic cleaner utilized was the Vevor 22-liter capacity cleaner, this had the added benefit of allowing control of duration of the cleaning cycle and temperature control of the fluid. For the most efficient removal of the support additional heat could be applied. The fluid beginning at 30C and running for two cycles of 12 minutes to allow for rearrangement of the parts was noted as the best cleaning method. While the support wax was quickly removed the IPA would develop a green tint indicative that the wax pattern was affected by the cleaner. To ensure adequate accounting for dimensional accuracy of the wax pattern, tests were performed to determine any loss of material. The tests consisted of two shapes, cylindrical and cuboid, see figure 14. The shapes allowed for

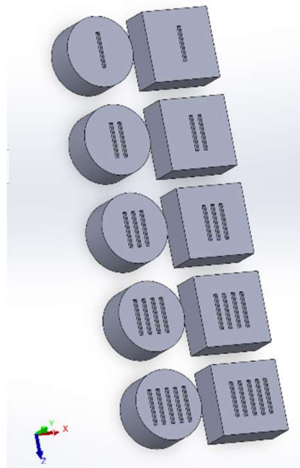


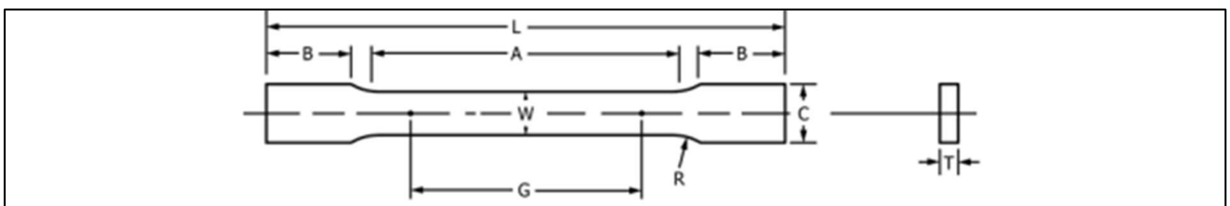
Figure 14. Specimens developed for Dimensional Loss due to Isopropyl Alcohol

determination of loss along straight faces and curved surfaces. Percent difference was determined using the following equation.

$$Percent\ Difference\ (\%) = \frac{Dimension_{Measured} - Dimension_{Model}}{Dimension_{Mod}} * 100$$

This indicates a loss of material as a negative percentage, the tests that were performed were variations on IPA content and time of soak. These tests validated if any excessive material loss would occur by using large volume of IPA and if the patterns remained in the IPA for extended periods of time. Upon completion the data was analyzed to determine if any additional scaling factors were necessary for model generation.

To determine if the wax would have substantial strength and to determine optimal build orientation tensile testing of the pattern wax was performed. Subsize tensile samples were generated in accordance with ASTM B557 – 15 [29]. This specification covers tensile testing of wrought and cast aluminum parts, and was utilized for generation of witness coupons that would be used to verify the casting procedures. As these tests were being done with wax, they do not meet the intent of the specification, but allowed for an adequate comparison as the models were the same dimension and care was taken to measure cross sectional area, see figure 15. The tensile testing occurred using Instron Bluehill software in conjunction with an Instron 5900 series tester. The strain rate was maintained at 2mm/minute, and graphs displayed the load and extension, in Newtons and millimeters respectively. To determine the optimal orientation of the wax pattern creation two wax samples were created in each orientation of building layers, see figure 16. These orientations showcased the variation in interlaminar strength of the wax by varying the cross-section of the layers. This also allowed the placement of the patterns in the build box to account for the highly desired features being produced in the strongest orientation.



	Dimensions, in.	
	Standard Specimen Sheet-Type, ½-in. Wide	Subsize Specimen ¼-in. Wide
G—Gage length	2.000 ± 0.005	1.000 ± 0.003
W—Width (Note 1 and Note 2)	0.500 ± 0.010	0.250 ± 0.002
T—Thickness (Note 3)	thickness of material	thickness of material
R—Radius of fillet, min	½	¼
L—Overall length, min (Note 4)	8	4
A—Length of reduced section, min	2¼	1¼
B—Length of grip section, min (Note 5)	2	1¼
C—Width of grip section, approximate (Note 2 and Note 6)	¾	⅜

Figure 15. ASTM B557 – 15, Dimensional Requirements for Tensile Specimens

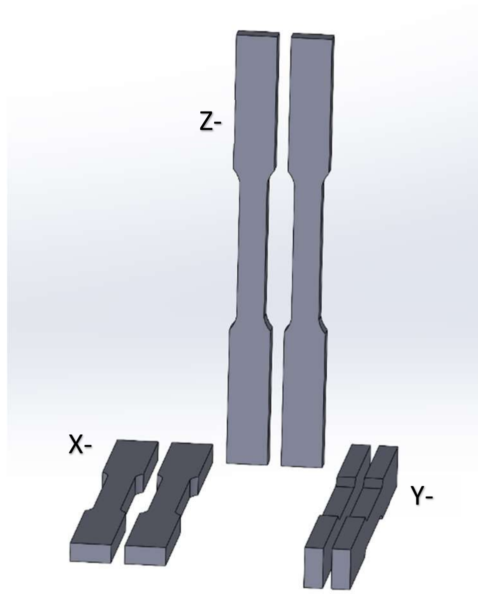


Figure 16. Build orientation of Wax Tensile Samples; X-, Z-, and Y-. Print head motion is length of X and Y Sample.

With this knowledge of the scaling factors and orientation the necessary model generation occurred. Due to the complex nature and size of the part it would have been unreasonable to perform the testing on a full-scale component. Instead, the part was scaled to 50% by volume, this would maintain the complexity but decrease the time of processing for sufficient sample being created. In accordance with design principles of the casting models the parts also required the addition of risers, sprue, and vents to ensure adequate flow [5]. The design of the riser was performed in accordance to Chvorinov's rule [28]. However, the important parameter for riser sizing is simply the solidification modulus, M.

$$T = B * \left(\frac{V}{SA}\right)^{n} \qquad M = \frac{V}{SA}$$

T=Solidification Time, B=Mold Constant, n = Constant,

M=Solidification Modulus, V=Volume of Casting, SA=Surface Area contacting mold

The principle behind the modulus is that the part requires a quicker solidification time than the riser. Therefore, the surface area being higher allows the pattern to solidify quicker, the riser must have a larger modulus indicating that the surface area is lower and heat loss will occur slower. This allows the riser to feed molten metal into the part to account for the shrinkage experienced from the phase transition of aluminum from molten to solid. The riser feeds until the path into the part is solidified and as such the use of an integrated riser was implemented. This implementation allowed for feeding of the riser into the thickest portion of the pattern for the entirety of solidification occurring. Riser design occurs for the initial shrinkage experienced in casting operations; the second shrinkage factor is the thermal expansion experienced from the metal being at a high temperature in its solid form. As the material cools the material will shrink, this thermal shrinkage is more commonly referred to as pattern maker's shrinkage. This is due to the correction occurring from increasing the size of the pattern to allow for the shrinkage while still maintaining the required dimensions. For aluminum alloys this shrinkage varies based on alloy, as our casting operations would not be specific alloy the shrinkage factor used was 1.8% [5].

As the model generation was completed the following step was the sprue and venting design. Two designs were used throughout the project, the initial version had issues in accordance with gas entrapment and dimensional losses as the mold was unable to be filled properly. The second design was developed to ensure adequate gas evacuation, by use of the traditional sand-casting flow design. This required the feeding of aluminum into the lowest portion of the mold and then the molten aluminum filling from the bottom until aluminum evacuated through the vents, see figure 17. Some additional features were implemented in version 2 allowed for easier storage and post processing capability, but were removed during ceramic shell creation. These two models are compared via the dimensional tolerances achieved, but no turbulence or flow study was performed.

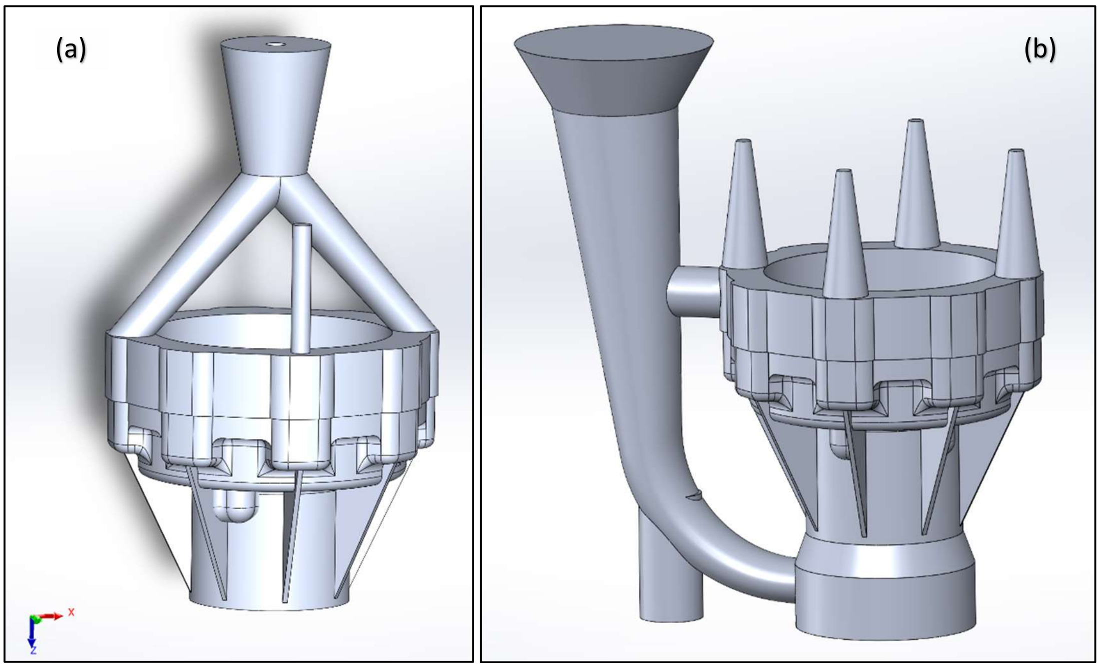


Figure 17. Modeled Geometry; (a) Version 1; (b) Version 2

Upon the wax patterns being completed they can then be coated with an investment casting Shell. The materials utilized were Suspend-a-slurry produced by Ransom and Randolph, which was developed to have increasingly easy operation. This slurry in conjunction with the Ranco-Sil fused silica creates the ceramic shell that can be then used as an aluminum mold. As discussed by Yao, the thickness of the shell is critical parameter to ensure no shell cracking occurs [24]. To adequately account for this the slurry was prepared and routinely applied. The Ranco-Sil sand utilizes two different grain sizes to ensure highest dimensional accuracy followed by higher strength capability. The finer grain size, was applied twice per pattern a minimum of 4 hours apart to ensure complete drying of the layers. After these layers are applied the large grains were utilized and did not require the same length of time between coats. Instead, a 2-hour regime was followed until the patterns had achieved a minimum of 6 coats. These coatings were then allowed to sit for 2 days to ensure adequate drying before wax removal. Upon wax removal cracking was shown to occur, to correct these issues additional patterns were created and between coats 3 and 4 wire was applied as reinforcement, as reinforcement was confirmed to increase strength of the ceramic [25]. Other important changes to the slurry were that between the first and second casting operation the slurry was vacuum sealed to remove any gas bubbles that could have been present in the slurry. This vacuuming remained constant at 25inHg for 48 hours to ensure all gas was evacuated, see figure 18. The slurry remained under vacuum any time it was not in operation.

Figure 18. Displays the vacuum and lack of bubbles along the surface of Suspend-a-Slurry

The removal of wax requires careful control of parameters, as the wax will expand prior to melting. The first step is to ensure wax escape of the ceramic shell, this is done by removal of the ceramic shell obstructing the sprue, and the addition of vent holes into the ceramic. Initial attempts to perform wax removal utilizing 175C oven and container to catch the molten wax were unsuccessful. As the wax was not vaporized the expansion occurred and applied increased stresses on the ceramic. To minimize the impact that the ceramic shell experiences the use of boiling water bath for wax removal has been found the most effective. The water applies isostatic pressure and ensures the ceramic shell is able to sufficiently handle the expansion of the wax. As the wax is hydrophobic it attempts to vacate the water and in turn coalesces on the surface of the water for easy removal. The use of water removal procedures did require an increase in the drying time of the ceramic as some expedited attempts resulted in the dissolving of ceramic and the loss of pattern capability. The molds were removed from the water and allowed to dry for a minimum of 1 hour to allow any release of water prior to firing that would cause pressure and rupture of the ceramic shell. The furnace operations were determined upon recommendation of Ransom and Randolph instructions of firing the ceramic shells at 925C for 1 hour. The firing stage performed multiple operations; any residual wax will be burned out due to the high heat. This also removes any residual moisture in the mold, solidifies the shell, increases its rigidity, and ensures no loss of dimensional accuracy when the aluminum is poured into the mold. Once the ceramic shells have been fired, they must be checked for cracks or deformities that will not allow them to be used for casting. This has been done by water test. After the shells are completed and preparations began to complete the casting operations, the molds are inserted into traditional sand molds to hold in the proper orientation. This also ensures no failure of the shell upon the aluminum entering the shell, from the thermal shock, by holding the shell in place regardless of any preexisting cracks.

Cautions were taken for the sand packing to protect the sprue and vents from sand entrance prior to creation of the funnel that would lead aluminum into the mold. The vents required more care as the vents were below the final sand level and would allow substantial sand without some protection. The aluminum furnace is initiated and melting begins, the aluminum alloy was unknown due to the use of recycled aluminum from various other manufacturing procedures to include, machining, milling, and casting. In an effort to increase the fluidity superheat was implemented as discussed by Santhi [7]. This superheat requires the aluminum reach a minimum temperature of 665C+/-5C. At this point casting can begin, two ceramic shells will be filled per pour and a tensile sample, per requirements in figure 15. The tensile sample will then be tested in accordance with ASTM B557 – 15 [29]. This will allow a verification of the casting procedures and determination as to the acceptance of aluminum alloy composition.

Additionally X-ray Fluorescence testing was performed to determine exact chemical composition. The XRF scanned the sample and would have detected any elements from Boron through Uranium. These results will allow for alloy determination and comparison to the desired aluminum of the study, C355. The surface finish of the as cast specimens was especially important in comparing and displaying the benefits of additive manufacturing. Due to time constraints this analysis was unable to be performed and will be attempted in the follow up research.

A dimensional comparison study was performed to determine the accuracy of the process and results to those of the model. This dimensional comparison required choosing key points of interest to compare across all cast parts. These standard dimensions chosen would be used to determine which version of casting tree was able to achieve better dimensional accuracy. After removal of the sprues, vents, and gating systems the measurements were taken according to figure 19. The use of five measurements and 3 visual examinations were used to simplify the comparison procedures. 3 unconstrained locations, 2 constrained locations, and 3 visual features. This also had the benefit of determining if the trees had substantial alteration in the complexity capabilities, gas entrapment, and contamination of molds. Porosity is a key parameter in regards to the casting process. Increase in porosity of the cast parts indicate poor gas evacuation which can be tied to an inadequate sprue and vent design, see figure 17a and 17b for the model. A comparison was also accomplished to determine the effect of slurry on the surface finish and dimensions. The comparison consisted of the use of first version of model being unvacuumed that was compared to an identical model in which the slurry was vacuumed. Continued comparisons were done in relation to the combined effect of the model revision and vacuumed slurry. All of these procedures utilized the same measured values of dimensional comparison with modifying the samples in accordance to the investigated parameters. This dimensional study is necessary to create a valid comparison of multiple parameters that could have affected the final part, and then would also be necessary to create a comparison across multiple additive manufacturing assisted procedures and not solely a comparison of the Investment casting process.

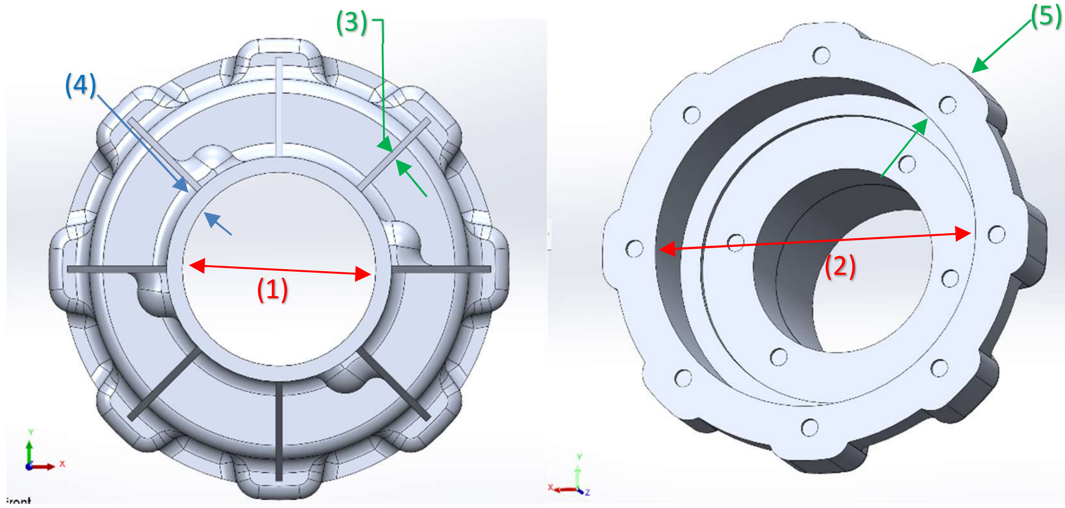


Figure 19. Location of desired dimensions: Constrained – (1) Upper Diameter; (2) Lower Diameter; Unconstrained – (3) Flange Thickness; (4) Upper Thickness; (5) Lower Thickness

Sand Casting – ZCorp 310 & 810

In an effort to continue the comparison of the Binder jet assisted sand casting manual creation of important test specimens was attempted. Primarily the determination of Tensile strength, transverse shear and permeability was desired. These are the major parameters that have been shown to affect the mold shrinkage, dimensional accuracy, and gas entrapment [8-16]. The manufacture of molds, that could be utilized to create the desired test samples occurred. These molds were then cleaned and coated to allow removal of the samples. The initial calculation of binder to volume ratio was unsatisfactory and in turn the use of provided ratios from the ZPrint Software was utilized. This gave a linear formula that denotes the ratio of binder to volume of part for shell and core. These equations are not identical as the shell will require higher strength and the core allows for higher permeability measurement [10-13][18]. While manual creation of samples did allow for margins of error and the lack of laminate structure efforts were taken to create acceptable samples. However, a drastic difference between the measured density of the dry sand and the density of binded sand. This density change results in an increase in the packing efficiency of the sand when wet. This is in opposition to other the density results by Martinez [17]. This likely occurs from the mixing and packing force of the sand into the molds, as the sand is unable to reconfigure itself in the additive manufacturing procedure as the binder is applied. Due to an inability to adequately disperse the binder without additional force, the process was ended and no further study was able to be done in regards to the Binder Jet assisted Sand casting.

CHAPTER V

FINDINGS

As the comparison of the Investment casting to Sand casting was unable to be sufficiently fulfilled due to the inability to generate sand molds. The findings will be in regards to process improvements researched for use during additive manufactured assistance of investment casting. The use of VisiJet M2 ICast wax was required and as such the determination of effect of Isopropyl alcohol for post processing was required. The results of a dimensional comparison to the model after prolonged exposure to IPA is shown in figure 20. The samples were tested at 4-hour increments, with a consistent volume of IPA. These results indicate that the loss of wax and the effect on dimensions is very minimal in the case of cylinder height and the cuboid width. The other dimensions are seen to be less predictable and as such could have experienced issues in regards to residual support wax remaining, or build orientation causing dimensional degradation is a preferred direction. The determination for the scaling factor was not in regards to the time spent in the IPA and to maintain quick removal of the wax parts.

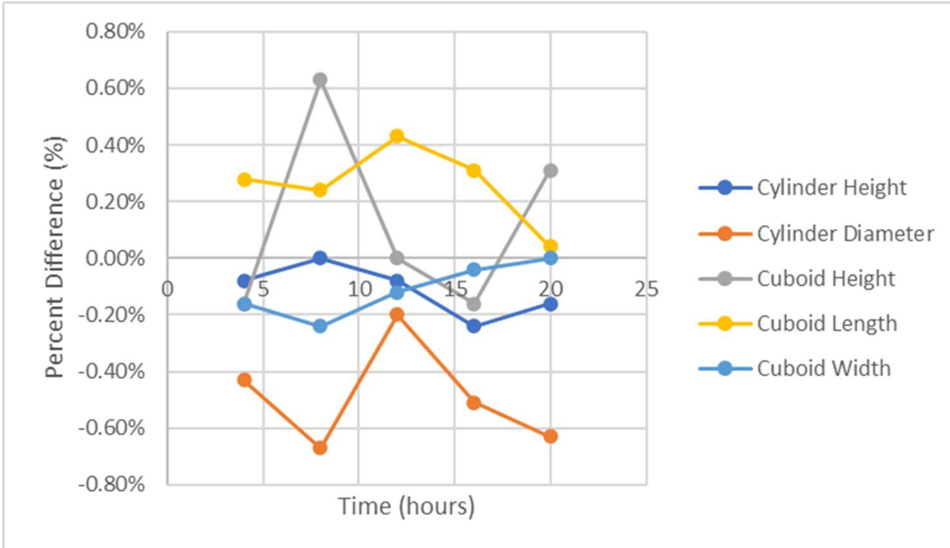


Figure 20. Dimensional Loss of Cylinder and Cuboid Wax Pattern with Prolonged Exposure

The results of dimensional loss due to excessive volume of Isopropyl alcohol was also performed. The results from this study are displayed in figure 21. The results are displayed in accordance to the mass of IPA, as this was the method of measurement that was utilized, and the samples remained in the IPA for 2 hours. The results from this study indicate that when the IPA is increased in relation to the size of the part the dimensional loss is consistent. The outlier that occurs was due to the unsatisfactory removal of support wax at the lowest volume. There is no point where the IPA will remove the wax to a great enough degree that IPA level needs to be modified in accordance to part size inside the ultrasonic cleaner. These results also indicate a more consistent result in dimensional loss and as such the scaling factor was chosen to be imparted into the model geometry. This scaling factor would account for the dimensional loss from post processing, and the results indicated a very similar loss with little to no dependence on the geometry of the surface. The average of these values was taken and the scaling factor of negative 0.25%-dimensional loss was utilized, resulting in a 0.25% Increase in the model geometry.

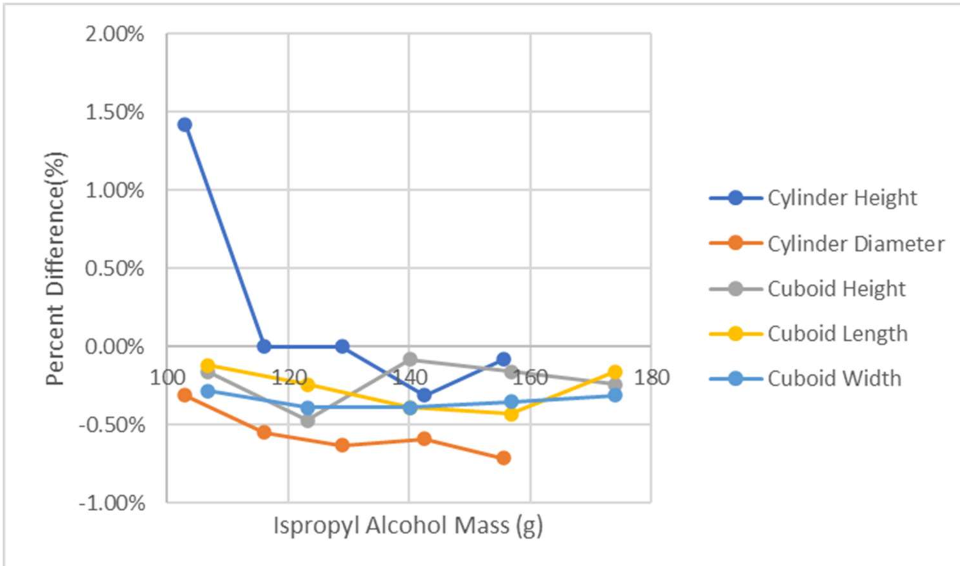


Figure 21. Dimensional loss of Wax Pattern, when Isopropyl Alcohol is increased

The wax strength was also determined to increase the capability of wax patterns and reduce the failures that would occur of important dimensions. These results are displayed in figure 22, only the load was determined as the production of the samples enabled accuracy of the cross-sectional area of failure to higher precision than the available measuring devices. These results showcase that similar to standard additive manufacturing techniques the weakest dimension is the Z-direction. This has an approximate break point of 15-20 newtons. The discrepancy between Z-1 and Z-2 are due to the delamination of the layers within the gripping mechanism and the subsequent sliding of the sample. The more anticipated values are those of Z-2 which indicate a single and swift delamination between two layers. The X-1 sample showed signs of preexisting issues from processing and handling. This was due to some deflection that was seen and may have caused cracking or delamination that reduced the cross-sectional area of load transfer. The results from X-2, and both Y samples followed the expected pattern of loading. This is the initial load and then some plastic deformation before final failure in the necked region of the tensile sample. These results showcase and confirmed that the Z-direction is the weakest direction and therefore the features of highest simplicity should be positioned in that direction. This also allowed for the model to be positioned in the most efficient wax usage position. With the conclusion of the wax testing the remaining tests and dimensional comparisons only affected the aluminum samples prepared by casting.

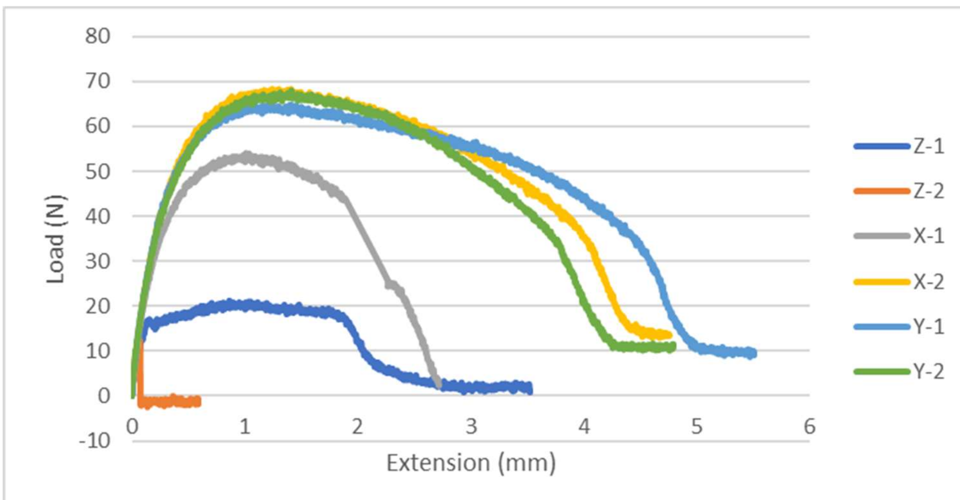


Figure 22. Tensile Strength of Visijet M2 ICast Wax based on Build orientation

When the casting operations were performed and the aluminum was removed from the mold the first determination needed was the chemical composition. This chemical composition shown in Table 1, allowed for the determination of if C355 was a comparable alloy and for determining approximate Tensile strength of the alloy. Chemical breakdown of aluminum alloy C355, was found per HS750 [30].

Cast Material	
Element	Amount
Aluminum	89.00
Copper	0.5500
Iron	0.3270
Silicon	0.6980
Magnesiun	1.1400
Manganese	0.1320
Zinc	1.1400
Titanium	0.0525
Carbon	3.7100
Oxygen	3.0100
Cromium	0.0997
Calcium	0.0377
Sulfur	0.0298
Iodine	0.0201
Potassium	0.0192
Gallium	0.0126
Nickel	0.0092
Zirconium	0.0073
Bismuth	0.0070
Phosphoro	0.0064
Arsenic	0.0028

Table 1. Cast Aluminum Composition and Alloy Comparison[1]

The results of the chemical composition indicate this material is unable to be classified as C355, and requires further research into other possible alloys. One important thing of note though is the carbon content of the aluminum, as carbon is not a traditional alloy element of aluminum. This plus the addition of Oxygen in the composition is indicative of some contamination of the sample prior to performing the XRF testing. This likely occurred during the preparation phase as the sample was deburred and removed cut marks using simple steel file. This file may have had residual contents of previous metals. Oxygen content could have been due to the cleaning system of utilizing the ultrasonic

[1] Complete aluminum comparison removed further requests fielded by Author.

cleaner and pure water to remove any cutting residue. This water could have penetrated and remained stuck in the sample, and as Hydrogen is unable to be measured via XRF the result is solely oxygen being detected in the sample. Due to these results being non-conforming to the C355 alloy the tensile samples were analyzed without respect to a specific alloy. Instead, the tensile results were used to compare the individual pours and determine if any possible discrepancies could be noted about the pours. The results of the tensile strength are shown in Figure 23, and the Stress-strain curve for the samples is in Figure 24.

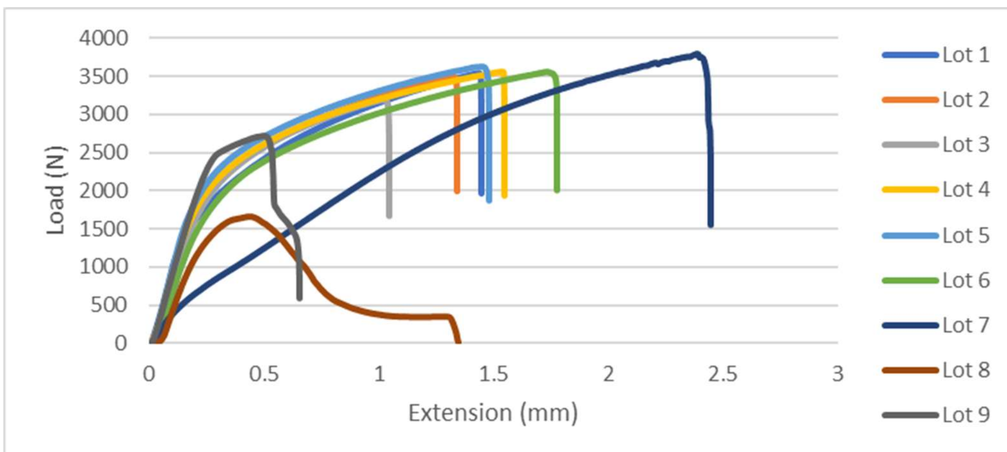


Figure 23. Tensile Strength of Cast Aluminum

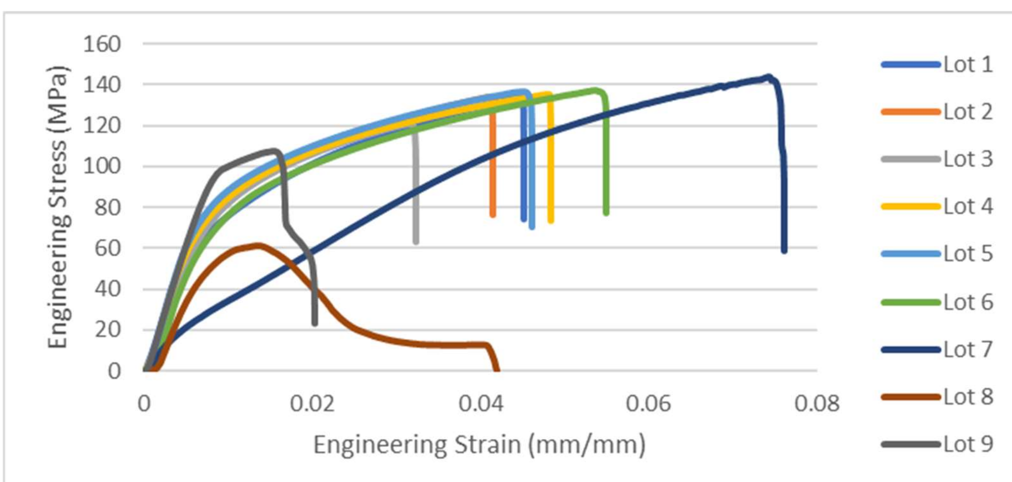


Figure 24. Stress-Strain Curve

The tensile strength and Stress curves are very similar but do display some interesting behavior based on the sample's tests. The initial casting operations results in Lot 1-6, which all display very similar tensile strengths and became even more closely clustered when accounting for any cross-sectional differences of the samples. The tensile strength of lot 3 is less than the others as it was noted to have sand inclusion within the fracture point. The second batch of cast parts show 3 results that are very dissimilar, Lot 7 has increased strength and extension, and did not experience large correction in regards to the stress-strain curve. This distinction can be noted to the possible increased cooling rate that occurred with Lot 7, during casting the sand surrounding Lot 7 was removed quickly after pouring and as such may have experienced a less than ideal cooling rate to maintain uniformity. Lot 8 had the initial curve following that of the first batch, however due to large porosity in the gripping area experienced loss of strength outside of the necked region. This resulted in distortion of the piece before finally failure of the specimen. Lot 9 was the most similar to that of the first batch, but when failure occurred examination of the sample indicated large sand inclusions. This sand inclusion reduced the cross-sectional area by approximately 50%. These results all indicate a very similar Ultimate tensile Strength, and the average excluding the specimens of abnormal failure shows 134.5MPa, with a standard deviation of 6.79MPa. When compared to the requirements of the HS750 specification tensile strength of{redacted}, which agrees and indicates a variety of issues with the aluminum alloy utilized.[2]

The comparison of the dimensional accuracy of the parts produced by investment casting has many portions of comparison. Further information in regards to the areas of

---

[2] The tensile requirements were redacted, due to being contained within a Distribution Statement D Document.

comparison is needed. Upon completion of the casting operations 8 key metrics were tracked, and broken into visual examination, unconstrained dimension, and constrained dimension. The visual examination occurred by counting the flanges clearly defined, interior holes clearly defined, and checking 3 random locations for interior ridge definition. The unconstrained dimensions were the thickness measurements taken, these occurred on the flanges if present, the upper bearing shaft, and the lower bearing housing. The constrained dimensions measured were the upper shaft diameter, and the lower bearing diameter. See figure 19 for exact locations of measurements. All of the locations measured had 3 random locations measured to ensure adequate sampling and a true comparison. With these metrics being tracked a comparison included: the slurry effect, model effect, and then a combined effect.

The first that needs to be looked into is the effect of the change in slurry processing. As the original batch did not receive any vacuuming and therefore allowed more issues with gas being collected on the surface of the model some of the dimensional results may have been affected. Shown in Figure 25, is the effect of vacuumed or unvacuumed slurry. The U refers to the upper portion of the part while the L refers to the Lower portion. The results show that the differences are primarily noted in the thicknesses of the part. The negative differences indicate that the part has smaller dimensions than those in the model, indicating higher shrinkage factors than were initially implemented into the model. The possible reason for this is any shrinkage that may have occurred upon the firing of the ceramic shell. However, the thicknesses measure may have been affected based on cutting and de burring operations. This would explain the lack of agreement among the samples and measurements. Important note is that the slurry effect did not remove the flange but in fact due to the flanges not being clearly defined there was no ability to measure the thickness of the flange. With that being said the effect of slurry did not seem great enough to negate the results of the model version changes.

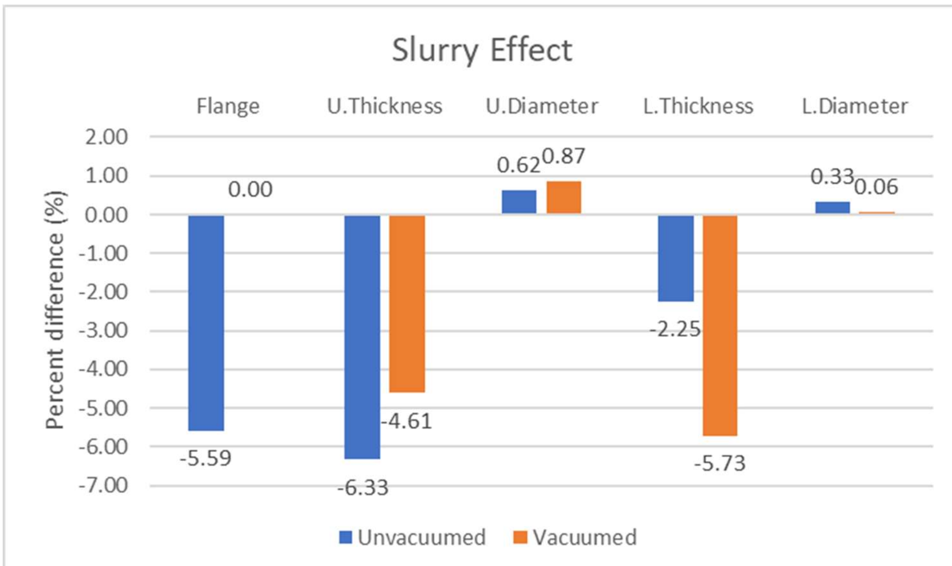


Figure 25. Effect of air evacuating slurry on dimensional change from model

The next comparison is in regards to the model version changes and the impact it made on the dimensional capability of the investment casting process. The intent of the revision change was to increase the prevalence of the complex geometries that the part displayed. In this regard the comparison began with the visual examination of features that were present, see figure 26. The measurement of these features required the addition of all detailed features present after casting, divided by the number of samples and features per sample. This showed the average of each model version despite some cast parts having no features and others all features present. This data indicates that an improvement was seen in all categories with the change from model version 1 to model version 2. A substantial increase was seen in that twice as many flanges were present, the interior holes experienced very little increase, while the ridge also had a good improvement to the definition. These two experiencing more definition are likely from the better gas evacuation seen in version 2, while the definition increase of the holes would have been primarily affected by better slurry preparation. These results also indicate that slurry had a very minimal effect.

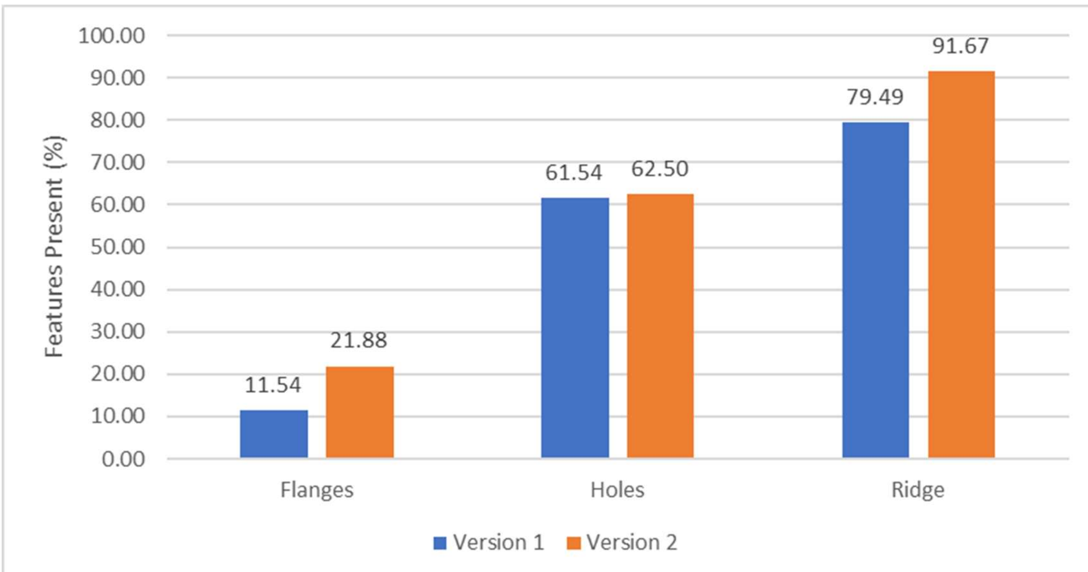


Figure 26. Comparison Model versions on Feature definition.

While the model is proven here to have an impact on part complexity, the dimensional accuracy must also be investigated to determine conclusively a better model. To ensure a comparison can be made with no impact by the slurry the use of solely parts cast with vacuumed slurry are utilized. The loss of dimensions measured by percent difference to model are displayed in Figure 27. A comparison can be made and indicates that the version 2 model has closer dimensions. The changes are not drastic in relation to the constrained dimensions, but in the unconstrained dimensions large corrections can be noted indicating the flow of fluid into this area is better and allows for better cooling and feeding by riser design.

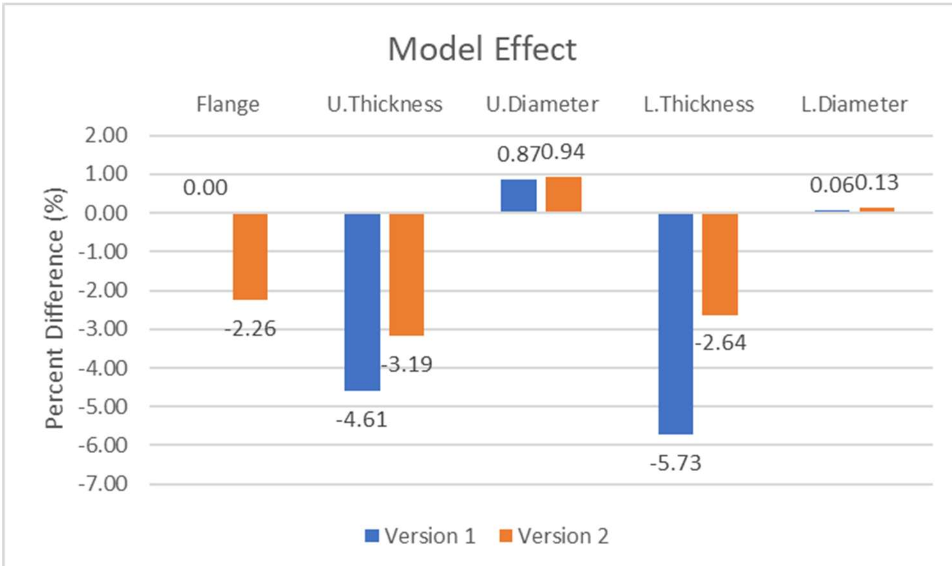


Figure 27. Dimensional Loss by Model version changes

The previous graphs showcase the model and slurry effect on the dimensional comparison of the cast parts to the model. However, the combined effects must also be noted as these could have impacted dimensions in undetermined ways. Shown in figure 28, the results indicate that the version 2 model created better dimensional control, as the variations seen throughout the graph were reduced. While the dimensions in version 2 were closer in proximity to each other indicating more accurate shrinkage ratios, the dimensions from version 1 for upper diameter and lower thickness were closer to desired values. This is likely due to air entrapment into version 1, as the gas would restrict filling into the upper shaft thickness, but the diameter would be maintained as it is a constrained dimension. The Lower thickness would have had a majority of the fluid being input into the mold for use as a riser and therefore could have been more adequately filled throughout solidification.

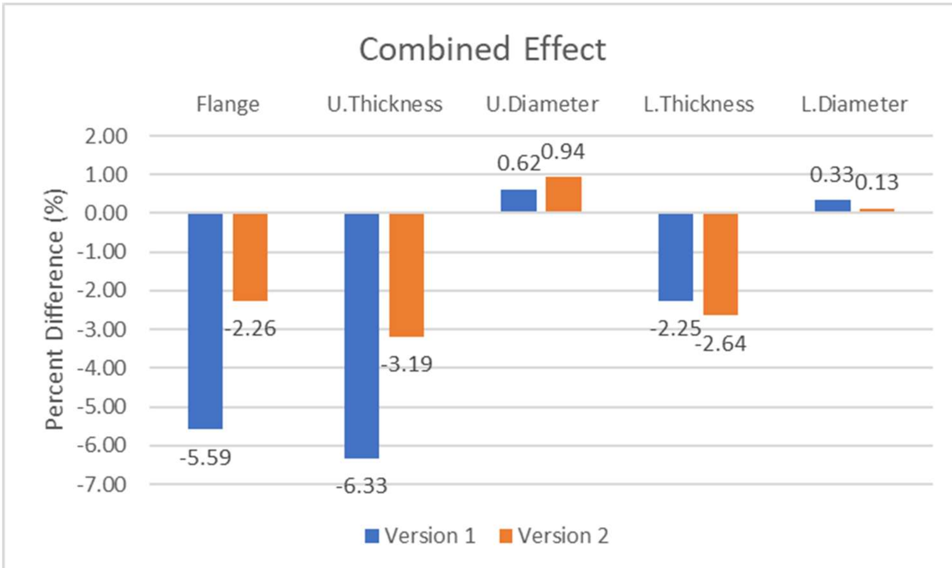


Figure 28. Overall Comparison of dimensional differences

From this dimensional comparison of the versions, the results indicate that model version 2 is the preferred model for investment casting. However, this does not indicate sufficient results to for determining success of the investment casting process as a dimensional loss of 3% thickness is unacceptable and further model adaptation needs to be accomplished to ensure dimensions meet requirements. The primary area of corrections lies in the design and validation of the riser. As the riser feeds the casting until complete solidification occurs and under the current version the loss of thickness is indicative of a loss of feeding prior to complete solidification.

CHAPTER VI

CONCLUSION

This paper has discussed the various differences and issues associated with additive manufacturing assisted casting procedures. The two forms of casting were binder jet assisted sand casting and polyjet wax pattern assisted investment casting. Both of these procedures have individual benefits and nuances that must be closely studied and understand for adequate casting production. In this study due to the lack of operational binder jet additive manufacturing equipment a true comparison was unable to be accomplished. Thus, in turn the polyjet assisted investment casting was performed, and process improvements implemented for analysis. This manufacturing method has been determined as the preferred approach for producing the desired bearing housing. Yet, this process does require increased understanding of the adaptations from traditional investment casting.

- Increased scaling factors must be adequately understood to account for Wax pattern shrinkage that occurs during post processing. The scaling factors are dependent on multiple parameters and must be determined for the wax in use, and post processing operations. This study solely covered the use of Visijet M2 ICast Wax, and processing occurring within Isopropyl Alcohol with a proof of 95+%.

- The strength of wax and its orientation upon the build platform will determine the handling capabilities of the wax pattern. Incorrect orientation on the platform will result in increased loss of dimensions and complications during ceramic shell buildup.
- Proper analysis of the casting design is a requirement for satisfactory part manufacture. This study was unable to correct the casting design to create full part complexity, but proved that with proper design complexity definition can be increased.

CHAPTER VII

RECOMMENDATIONS

Future research considerations rely heavily upon the completion of a comparison study between the binder jet assistance and polyjet assisted manufacturing. Primarily the complexity capability and the dimensional conformity that can be achieved. Other key points of research will be the determination of near net casting parameters. This refers to the surface finish and dimensional tolerance achieved to reduce the need for additional post processing after casting. The surface finish and dimensional tolerance will be affected by multiple process parameters and as such require further study. Sand casting will require in depth analysis of the sand properties, tensile strength, transverse shear, and permeability. As it has been proven all of these properties affect the casting production and properties. In relation to investment casting the continued study of ceramic shell creation, and application procedures to increase surface finish and strength are necessary before determining preferred method.

REFERENCES

[1] Mukhtarkhanov, M., Perveen, A., & Talamona, D. (2020). Application of stereolithography based 3D Printing technology in investment casting. *Micromachines*, 11, 946. https://doi.org/10.3390/mi11100946

[2] Sivarupan, T., Balasubramani, N., Saxena, P., Nagarajan, D., El Mansori, M., Salonitis, K., Jolly, M., & Dargusch, M. S. (2021). A review on the progress and challenges of binder jet 3D printing of sand moulds for advanced casting. *Additive Manufacturing*, 40, 101889. https://doi.org/10.1016/j.addma.2021.101889Additive Manufacturing

[3] Bandyopadhyay, A., & Bose, S. (2020). Additive Manufacturing (Bandyopadhyay & S. Bose, Eds.; Second edition.). CRC PRESS.

[4] Francis, L. (2016). Materials Processing: A Unified Approach to Processing of Metals, Ceramics and Polymers. Elsevier Science & Technology. https://doi.org/10.1016/C2009-0-64287-2

[5] Sigworth, G. (2014). Shrinkage, Feeding and Riser Design. 118th Metalcasting Congress. https://www.researchgate.net/publication/267343777_Shrinkage_Feeding_and_Riser_Design

[6] Saxena, S., & Sharma, P. (2017). Casting Fluidity of Metals and Alloys. *International Journal of Innovative research in Science and Technology.* 6, 2. http://www.ijirset.com/upload/2017/february/171_CASTING.pdf

[7] Timelli, G., & Caliari, D. (2017). Effect of Superheat and Oxide Inclusions on the Fluidity of A356 Alloy. *Materials Science Forum*, 884, 71–80. https://doi.org/10.4028/www.scientific.net/msf.884.71

[8] Santhi, S. (2018). Calculation of Shrinkage of Sand Cast Aluminum Alloys. *International Journal of Applied Engineering research.* 13. 11.

[9] Kearney, A. & Rooy, E., (1990). Aluminum Foundry Products. *ASM Handbook.* Volume 2. 123-151

[10] Khandelwal, H., & Ravi, B. (2015). Effect of Binder Composition on the Shrinkage of Chemically Bonded Sand Cores. *Materials and Manufacturing Processes*, 30(12), 1465–1470. https://doi.org/10.1080/10426914.2014.994779

[11] Gyarmati, G., Budavári, I., Fegyverneki, G., & Varga, L. (2021). The effect of sand quality on the bending strength and thermal distortion of chemically bonded sand cores. *Heliyon*, *7*(7), e07624–e07624. https://doi.org/10.1016/j.heliyon.2021.e07624

[12] Mitra, S., Rodríguez de Castro, A., & El Mansori, M. (2018). The effect of ageing process on three-point bending strength and permeability of 3D printed sand molds. *International Journal of Advanced Manufacturing Technology*, *97*(1-4), 1241–1251. https://doi.org/10.1007/s00170-018-2024-8

[13] Coniglio, N., Sivarupan, T., & El Mansori, M. (2017). Investigation of process parameter effect on anisotropic properties of 3D printed sand molds. *International Journal of Advanced Manufacturing Technology*, *94*(5-8), 2175–2185. https://doi.org/10.1007/s00170-017-0861-5

[14] Khandelwal, H., & Ravi, B. (2016). Effect of molding parameters on chemically bonded sand mold properties. *Journal of Manufacturing Processes*, *22*, 127–133. https://doi.org/10.1016/j.jmapro.2016.03.007

[15] Sivarupan, T., El Mansori, M., Coniglio, N., & Dargusch, M. (2020). Effect of process parameters on flexure strength and gas permeability of 3D printed sand molds. *Journal of Manufacturing Processes*, *54*, 420–437. https://doi.org/10.1016/j.jmapro.2020.02.043

[16] Anwar, N., Sappinen, T., Jalava, K., & Orkas, J. (2021). Comparative experimental study of sand and binder for flowability and casting mold quality. *Advanced Powder Technology : the International Journal of the Society of Powder Technology, Japan*, *32*(6), 1902–1910. https://doi.org/10.1016/j.apt.2021.03.040

[17] Martinez, D., Bate, C., & Manogharan, G. (2020). Towards Functionally Graded Sand Molds for Metal Casting: Engineering Thermo-mechanical Properties Using 3D Sand Printing. *JOM (1989)*, *72*(3), 1340–1354. https://doi.org/10.1007/s11837-019-03975-x

[18] Sundaram, D., Svidró, J. T., Svidró, J., & Diószegi, A. (2021). On the Relation between the Gas-Permeability and the Pore Characteristics of Furan Sand. *Materials*, *14*(14), 3803–. https://doi.org/10.3390/ma14143803

[19] Mckenna, N., Singamneni, S., Diegel, O., Singh, D., Neitzert, T., St. George, J., Choudhury, A., & Yarlagadda, P. (2008) Direct metal casting through 3D printing: a critical analysis of the mould characteristics. 9th Global Congress on Manufacturing and Management.

[20] Kumaravadivel, A., & Natarajan, U. (2012). Optimization of sand-casting process variables—a process window approach. *International Journal of Advanced Manufacturing Technology*, *66*(5-8), 695–709. https://doi.org/10.1007/s00170-012-4358-y

[21] Cheah, C.M., Chua, C. K., Lee, C. W., Feng, C., & Totong, K. (2005). Rapid prototyping and tooling techniques: a review of applications for rapid investment casting. *International Journal of Advanced Manufacturing Technology*, *25*(3-4), 308–320. https://doi.org/10.1007/s00170-003-1840-6

[22] Rooks, B., (2002). Rapid tooling for casting prototypes. *Assembly Automation*, *22*(1), 40–45. https://doi.org/10.1108/01445150210416664

[23] Wu, H., Li, D., Tang, Y., Guo, N., Cui, F., & Sun, B. (2009). Rapid casting of hollow turbine blades using integral ceramic moulds. *Proceedings of the Institution of Mechanical Engineers. Part B, Journal of Engineering Manufacture*, *223*(6), 695–702. https://doi.org/10.1243/09544054JEM1366

[24] Yao, W.L., & Leu, M. C. (1999). Analysis of shell cracking in investment casting with laser stereolithography patterns. *Rapid Prototyping Journal*, *5*(1), 12–20. https://doi.org/10.1108/13552549910251837

[25] Lu, Z.L., Fan, Y. X., Miao, K., Jing, H., & Li, D. C. (2014). Effects of adding aluminum oxide or zirconium oxide fibers on ceramic molds for casting hollow turbine blades. *International Journal of Advanced Manufacturing Technology*, *72*(5-8), 873–880. https://doi.org/10.1007/s00170-014-5723-9

[26] Wawulska-Marek, P., Sitek, R., Bolek, T. Zdunek, J., Mizera, J. & Kurzydlowski, K. (2015) A study on Technological Properties of Investment Casting Waxes. *Advances in Applied Plasma Science.* 10. 37-40.

[27] Yarlagadda, P., & Hock, T. S. (2003). Statistical analysis on accuracy of wax patterns used in investment casting process. *Journal of Materials Processing Technology*, *138*(1), 75–81. https://doi.org/10.1016/S0924-0136(03)00052-9

[28] Dwivedi, D.K., Fundamentals of Manufacturing processes. (August 13, 2017). *Casting: Riser Design* [Video]. YouTube. https://www.youtube.com/watch?v=2UzsJNIkZxY

[29] ASTM Standard B557, 2015. *Standard Test Methods for Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products,* ASTM International, West Conshohocken, Pa, 2015

[30] HS750, 1994, *Casting Aluminum Alloy, Premium Quality, Acceptance and Material Specification,* United Technologies Hamilton Standard, Windsor Locks, CT, 1994[3]

[3] HS750 is Distribution Statement D, Requests for document must be fielded by Tinker office AFLCMC/LZPEM

VITA

Jefferson Harrison

Candidate for the Degree of

Master of Science

Thesis: ADDITIVE MANUFACTURING ASSISTED CASTING METHODS FOR ALUMINUM

Major Field: Materials Science and Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Materials Science and Engineering at Oklahoma State University, Stillwater, Oklahoma in December, 2022.

Completed the requirements for the Bachelor of Science in Mechanical Engineering at Oklahoma State University, Stillwater, Oklahoma in 2017.

Experience:

Worked in the Aerospace sector since February 26th, 2018.