Applications of Investment Casting as a Manufacturing Process for Injection Mold Tooling

by

Lila N. Wine

Submitted to the
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Signature of Author: ______________________________________

Department of Mechanical Engineering
May 6, 2022

Certified by: ______________________________________

Daniel Gilbert
Technical Instructor in Mechanical Engineering
Thesis Supervisor

Accepted by: ______________________________________

Kenneth Kamrin
Associate Professor of Mechanical Engineering
Undergraduate Officer

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ABSTRACT

An exploration in the utility of investment casting aluminum molds for small-scale plastic injection molding, compared against traditional machining methods for these molds. The intention of this study was to determine if lost wax casting could provide a more efficient option for tool manufacturing. Complex patterns were designed and 3D printed using castable resin, following manufacturers specifications. Various parameters throughout each step of the casting process, such as part design, 3D print settings, and investment procedures were altered to determine their effect on the end result. In the end, more time is necessary to achieve the desired results given the resource limitations of this study. Investment casting could still be a viable option for this type of tooling, given adequate time and resources to optimize each parameter and create a highly repeatable process.

Thesis Supervisor: Daniel Gilbert
Title: Technical Instructor in Mechanical Engineering

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1 Introduction

1.1 Injection Molding

Injection molding is a manufacturing process used widely to mass produce parts and consumer products. The process is relatively new compared to other forms of manufacturing, as the first injection molding machines of the form still used today didn't appear until the 1940s [1]. Although it is possible to injection mold with a variety of materials, by far the most common of these materials is plastics, in particular thermoplastics such as polyethylene. The majority of all plastic products made today are injection molded, as it is an incredibly versatile and cheap method of manufacture [2]. Injection molded parts are present in almost every industry, from food handling to automobiles.

The injection molding process, at a high level, requires plastic pellets to be heated until they reach liquid form, and shot into a mold at a high pressure. Once the mold is filled, the plastic solidifies before being released from the mold, and the process begins again. Mold design is one of the main challenges of injection molding, and often represents a large portion of the cost of injection molded parts (particularly for lower volume production, where the cost of the mold tooling is divided among fewer parts) [3]. Molds can cost anywhere from a few hundred dollars for simple geometries to hundreds of thousands of dollars for large, complex parts, and are often quite challenging to design and manufacture. Molds must be designed in a way which allows the part to be created in the desired shape, while also allowing the part to be released from the mold. The simplest molds are comprised of two halves, the cavity and core, which come together along a parting plane to form the part. Figure 1 shows a two-part mold for a plastic cup. Often, plastic products require a multi-part mold to create complex geometries and avoid undercuts (the condition in which a plastic part could not be released from the mold).

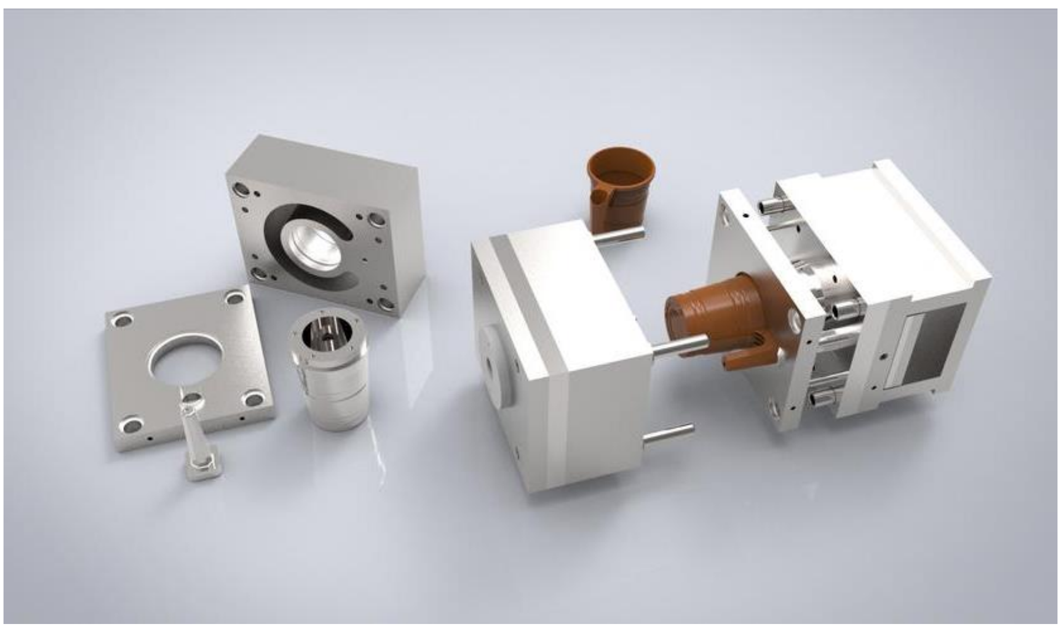


Figure 1: *An example of a two-part injection mold for a plastic cup [4].*

1.2 Injection Mold Tooling

The most common manufacturing method for injection mold tooling is machining, typically on a multi-axis CNC mill. As molds become more complex, the time and cost associated with machining them increases significantly. Typically, a smooth surface finish is desired for the finished plastic product, which requires the mold itself to have the same smooth surface finish. Achieving high quality finishes on contoured parts requires a lot of time dedicated to setting up the machining process and long machine toolpaths, which in turn drives up the cost of a mold. This means that manufacturers of injection molded parts must strive to get the mold right on the first try; if there are any major problems an entirely new mold must be made, costing the manufacturer lots of time and money.

1.3 3D Printing as an Alternative Manufacturing Method

Due to these limitations of machining, it is important to explore alternative manufacturing methods for injection mold tooling. Depending on the injection molding process used, it is possible to 3D print injection molds out of high strength plastics [3]. A benefit of 3D printing is its flexible prototyping abilities. Engineers can quickly test mold variations at low cost with 3D printing, with minimal added engineering time to design the mold (in fact, a technician would likely spend more time developing a machining process than they would setting up 3D print parameters for the same mold). These 3D printed molds are severely limited by the strength of the material, however, and are typically only suitable for low-volume production runs. 3D printed plastic molds cannot withstand the same temperature fluctuations that a machined metal mold could.

Another benefit of 3D printed molds is the added complexity and detail that 3D printing allows for. Additive manufacturing and 3D printing are very new manufacturing methods; the first 3D printers were developed in the 1970s and 80s, and 3D printing has not been considered a viable industry manufacturing method until the past decade or so. There are two main types of 3D printing, Fused Deposition Modeling (FDM) printing and Stereolithography (SLA) printing. This paper will focus on SLA printing over FDM printing, as it is generally the process used for making injection mold tooling due to its higher durability and better resolution (shown in Figure 2).

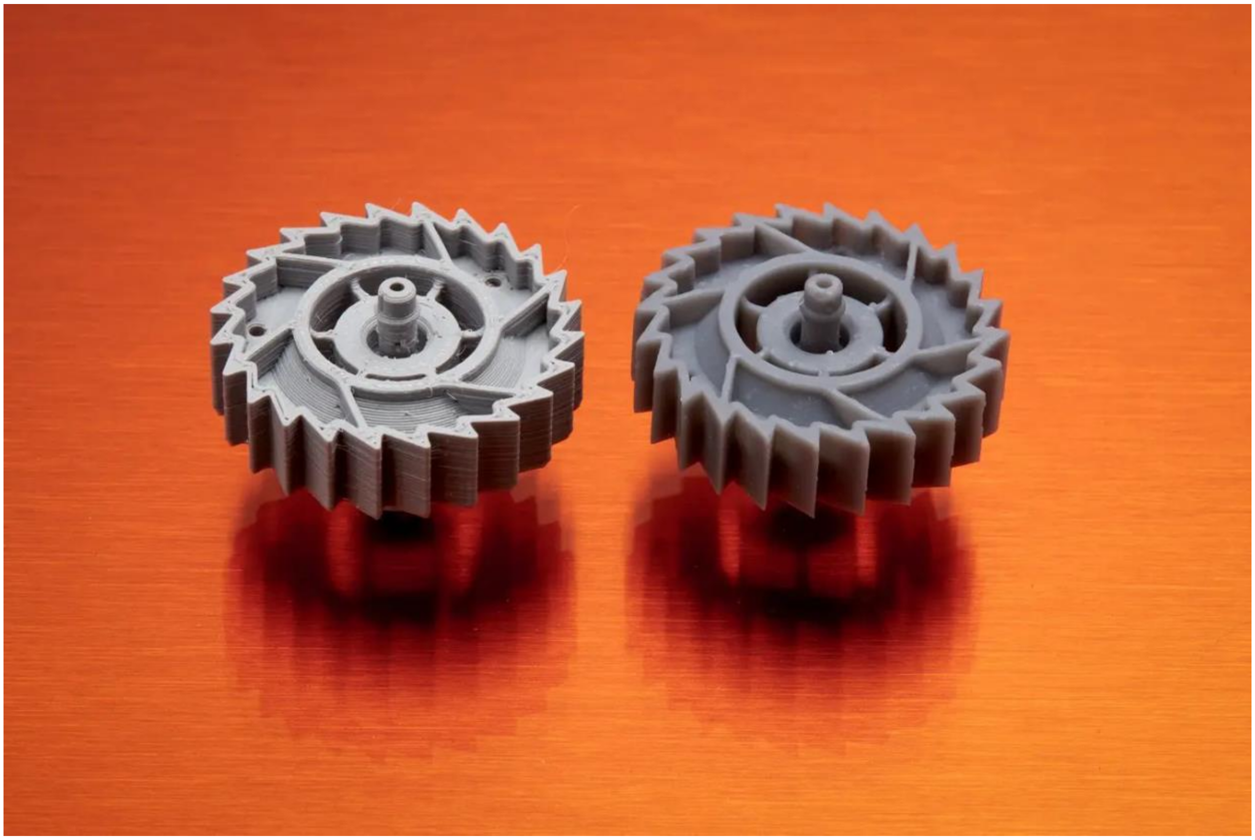


Figure 2: *A comparison of an FDM printed part (left) and a SLA printed part (right). The SLA printed part has a much higher surface quality and is generally more durable, though it is often more brittle than FDM printed parts [5].*

Affordable, consumer-oriented SLA printers (such as the one used in this study) can reach resolutions of as little as 150 microns (0.006”) in the X-Y plane and 25 microns (0.001”) in the Z direction [5]. This means that while all 3D printed parts will have some variation, in general, SLA printed parts will be repeatable and accurate to a degree desired for consumer and industry applications.

1.4 Investment Casting

In recent years, 3D printer manufacturers such as Formlabs have developed resins capable of being used in the investment casting process. In this process, a wax part is surrounded in a ceramic slurry and baked at a high temperature, so the slurry solidifies and the wax is melted out. Once all the wax material is gone and the ceramic shell has reached a sufficient temperature, liquid metal is poured into the ceramic mold and cooled, after which it is broken free from the mold and the resulting metal part is the same as the original wax part. Investment casting can produce very fine surface finishes if a smooth slurry is used, and is often used in jewelry making and precision part making for engines. There are many ways to create the original wax part; originally, the wax was carved by hand into the desired shape, now, the wax parts can be either cast themselves, machined, or 3D printed. 3D printing allows for the broadest range of possibilities for details and complex contours, with virtually no added time on the designers’ part.

While casting was once considered a time-intensive, low production volume process not suited for the mass production required for most large industries, recent improvements and developments to all kinds of casting processes are pushing casting back into industry norm. Investment casting, also known as lost wax casting, is one of the oldest known casting techniques. The earliest mentions of investment casting appear around 5,000 years ago, and although the process has varied in significant ways since then, the overall process remains relatively unchanged [6]. The general steps for investment casting are as follows [7]:

1. Create a pattern of the desired final part from wax.
2. Assemble wax pattern(s) into a wax tree by melting small surfaces of the wax and pressing them onto a sprue.
3. Coat wax tree in desired investment material (typically a type of ceramic).
4. Melt and burnout wax to create a negative investment of pattern.
5. Pour liquid metal into ceramic investment.
6. Once metal has solidified, break cast part free from investment.
7. Finish metal part to desired quality.

Investment casting can be used to create parts ranging from a few ounces to several thousand pounds [8]. Due to its high cost at low volume in comparison to other casting methods (such as sand casting or die casting), it is used more frequently for high-volume runs or to create parts that could not be cast using another method. Investment casting at small scale is most often used for jewelry making and can quickly create intricate designs that would take hours or days to shape by hand. Figure 3 shows an investment cast ring, from the first step of the wax pattern to the finished product. Though some post polishing is needed, the overall clarity of details as well as surface finish of the part straight out of the ceramic shell is extremely high quality. Other types of casting cannot compete with investment casting in this regard.

Figure 3: *An investment cast ring at all steps of the investment casting process [9].*

On larger scales, investment casting is used in industries ranging from aerospace to commercial products. SpaceX, an aerospace company responsible for over 60% of all orbital launches from U.S. soil in 2020 [10], uses investment casting to manufacture their rocket engines. The Raptor engine, designed for use on their Starship vehicle, utilizes a cast manifold, which was originally comprised of an estimated 100 individual parts that required assembly. Figure 4 shows a freshly poured Raptor part, as the glowing red from inside the ceramic shell indicates that the liquid metal has not yet fully solidified [11]. SpaceX utilizes 3D printed patterns to create their manifolds, and uses an automated production line to invest all parts. The flexibility and efficiency of investment casting allows SpaceX to iterate through designs quickly, without the need to spend large amounts of money on tooling that would be necessary for die casting or standard machining. In addition, flow simulation software can be used to optimize pattern designs, so that the time it takes to optimize casting parameters for successful casts is minimized. As aerospace is an industry with virtually no room for error, cast parts must be validated using various non-destructive evaluation methods. Internal defects cannot be seen without cutting open the part, which would ruin the part in itself. As the casting process is further refined, and a larger casting facility is built, SpaceX can increase it's production of Raptor engines, with the goal of producing up to 1,000 engines per year (more than 3 engines per day) [12].

Figure 4: *A recently poured Raptor manifold from the SpaceX Foundry [11].*

Since investment casting is such a useful process for creating complex, high quality parts, it is no surprise that it's use in industry (outside of craftsmanship) has expanded so greatly in recent years. This, combined with the increased quality and reliability of 3D printers, has opened up a breadth of possibilities that were once considered impossible. For example, before 3D printing, a jeweler would have to carve the wax pattern for a ring by hand, a process that could take many hours or days, and was prone to failure. With the capabilities of 3D printing and CAD software, a jeweler can design and test many iterations of a ring at once, and can be working on new designs as the 3D printer is running. Similarly, 3D printers can create massive assemblies that would previously be comprised of hundreds of pieces that would need to be hand assembled.

As casting becomes a widely used manufacturing process for things previously believed could not be cast, it is important to consider what other applications casting could be used for. Injection mold tooling also grows more complex as injection molding machines become more capable; what if investment casting could be used in conjunction with 3D printing to create this tooling in a more cost effective and efficient way? Investment casting has already been proven capable of achieving the high quality surface finishes needed for injection molding molds, and it can create more complex geometries than machining. In addition, aside from the actual pouring process, the 3D printing and slurry coating can be automated, to save immense amounts of time and money on human labor.

1.5 Investment Casting Quality

It is estimated that standard linear tolerances from investment casting result from 3 factors: shrinkage (20%), tolerances from the tooling (10%), and process variation (70%) [13]. While standard tolerances for investment cast parts are relatively large due to the variability of the process, it is possible to minimize these variations through good process control and well-tested parameterization. This parameterization is the driving factor behind investment casting costs, as it can take many iterations and trials to find a set of casting settings that work reliably for a desired part. Once these settings are found, however, it is more than possible to get highly repeatable accuracy.

The industry standard for investment casting processes is ±0.005" per inch of length [14]. This is a relatively easy bar to hit with good casting practices and good mold design. ISO-16468:2015 provides "technical requirements for castings (steel, nickel alloys, and cobalt alloys) produced by the investment-casting process" [15]. Although the metal used in this study was aluminum, the standards outlined here were a good starting place. The standard calls out requirements for materials, melting processes, part cleaning, and resulting part quality, along with many methods of non-destructive evaluation.

1.6 Context of Investment Casting in this Study

Since the scope of this investigation was limited by cost and material constraints, an already well-understood mold design was chosen for testing. The course 2.008, Design and Manufacturing II, taught to upperclassmen in MIT's mechanical engineering program, utilizes small-scale injection molding machines to teach students about various aspects of mass manufacturing. The molds used in these machines all share the same alignment and securing features, and are all machined from the same mold blanks. These molds were chosen to be tested as castings because of their proven reliability in the injection molding machine and their known methods of machining. In addition, existing stock used to machine the molds could be melted and used for the castings, ensuring that both cast and machined molds were made of the same material. A set of machined molds for the class, along with the associated injection molded part created by them, is shown in Figure 5.

(a) *(b)*

Figure 5: *(a) Two halves of an injection molding mold from the class 2.008, and (b) the resulting injection molded part.*

2 Experimental Setup

2.1 Overall Process

This investigation intended to follow a typical process for investment casting at low volumes using 3D printed wax parts. For each cast part, the following steps were to be taken to ensure consistency across parts and achieve high quality results:

1. Create a model of desired part using CAD software (Autodesk Fusion 360)
2. 3D print part on a Form 2 printer
3. Inspect 3D printed part using calipers and compare against CAD model
4. Add wax runners and sprue to part
5. Cast part in Suspendaslurry FS material
6. Burnout wax part and pour aluminum into mold
7. Inspect resulting cast part and perform any post machining necessary
8. Use part in injection molding machine and compare results against machined counterpart

The rest of this chapter will describe in detail the considerations taken at each step, and the following chapters will describe how these processes were altered between trials to ensure the highest chance of a successful part, and how certain aspects of the process failed, which resulted in the experiment being cut off after step 6.

2.2 Part Design

Autodesk Fusion 360 CAD software was used to model all molds, as the software also supports CAM features necessary to machine the counterpart molds. When modeling the molds, special care was taken to increase the chances of a successful cast part, as well as ensure they included the necessary features to integrate into the injection molding machine (even if those features would later have to be remachined). All parts were given the necessary bolt clearance holes and locating pin holes so they could be inserted into the existing mold inserts, shown in Figure 6.

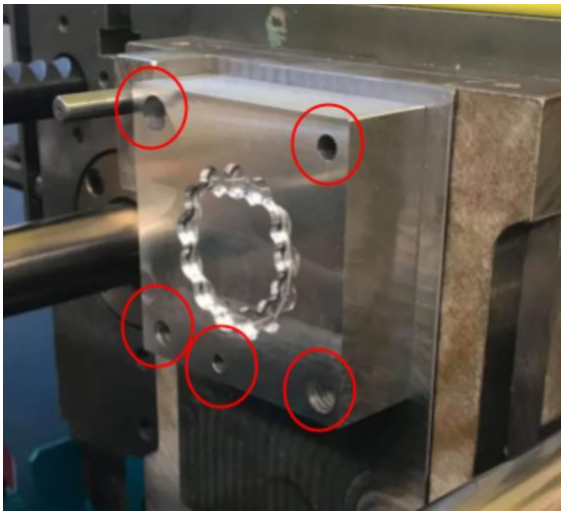


Figure 6: *An injection molding mold for a 2.008 yoyo, with critical holes circled in red.*

In addition, the molds were modeled off of the existing mold blanks for machined molds, to ensure that a counterpart machined mold could be made without the need for special stock or fixturing. Finally, molds were modeled using surface modeling, to create complex contours that could be easily created by the 3D printer, but would be difficult and time consuming to machine.

2.3 3D Print Process

Before printing, parts were scaled up to account for shrinkage from printing, as well as shrinkage from casting. Using Formlabs software Preform, parts were oriented on the build platform and rafts were added to support overhangs and increase the likelihood of a successful print. The Form 2 printer was loaded with Formlabs Castable Wax Resin, a resin designed specifically for investment casting. This resin costs $299 per 1 liter cartridge at retail, though the resin used in this experiment was gifted by Formlabs for no cost. After printing, the part was removed from the build platform and washed in an IPA bath for 6 minutes, following the specifications for Castable Wax Resin provided by Formlabs. The resin did not require any post print curing.

After the part was cleaned and dried, all raft and support material was removed. This was a particularly manual process, requiring the use of a bandsaw and pliers to remove all rafts. It took about 30 minutes per part to remove all support material. Figure 7 shows a section of removed raft material with the part it was removed from. Once all excess material was gone, the critical dimensions of the part were measured using calipers. Critical dimensions typically included overall length and width of the part (these dimensions did not change across molds), as well as any hole diameters and other boss or bore dimensions. These dimensions were then compared against the expected dimensions from the model to characterize the shrinkage from 3D printing.

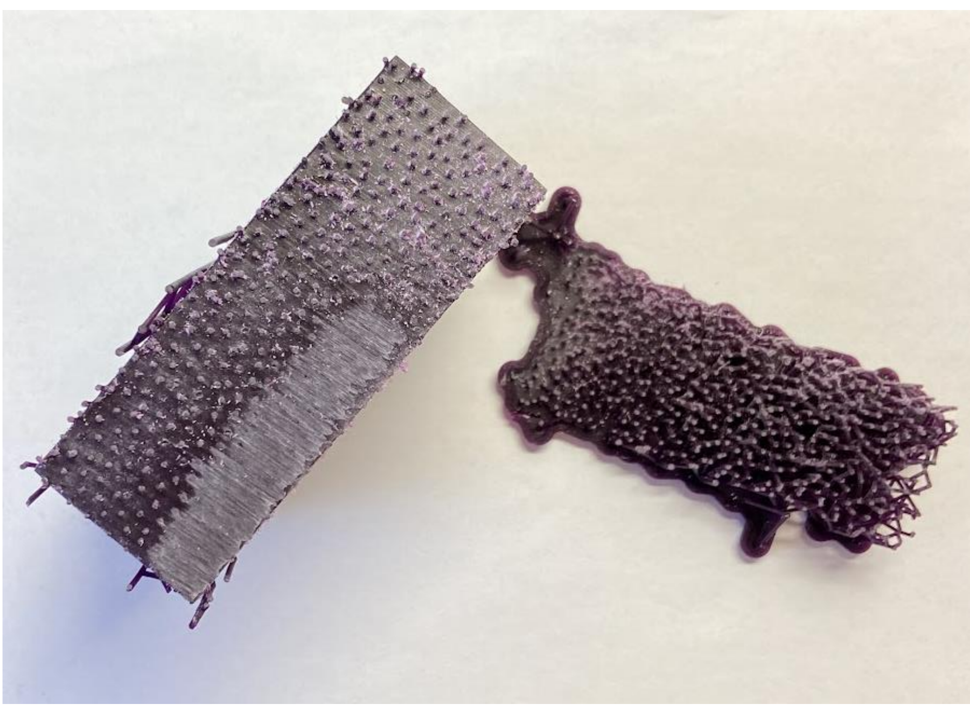


Figure 7: *A 3D printed part (left) and the raft material removed from it (right).*

2.4 Casting Process

Once all critical dimensions were measured and deemed satisfactory, the next step was to add the wax sprue and runners to the printed parts. Different configurations were used on different parts to test optimal orientation. In general, at least one runner was attached to the part on a non-critical face by melting the end of the wax wire and pressing it into the part until it solidified. Once all the runners were added, a larger sprue was added, connecting all the runners and creating a pour location.

After the full mold with runners and sprue was ready, the part was then cast in Suspendaslurry FS material. Figure 8 shows the dipping and coating setup used. The slurry was mixed with an electric drill before each dip to ensure no settling had occurred and that the slurry was at the correct viscosity. Then, a part was dipped in the slurry and drained until only a thin layer of slurry remained. Next, Ranco-sil A fused silica sand was poured over the part until it was completely coated. Following the first coat, Ranco-sil B fused silica sand was poured over the backup coats. The part was allowed to dry completely between coats, as indicated by the shifting in color of the slurry material. Parts were coated with 2, 3, and 4 backup coats to test the effectiveness of adding more coats to strengthen the mold.

(a) (b)

Figure 8: *(a) A part about to be dipped in Suspendaslurry FS material, and (b) a part after being coated with Ranco-Sil B fused silica sand.*

After parts were cast and slurry coats were fully dried, parts were placed in a small, temperature controlled furnace for wax burnout. All parts followed the burnout schedule provided for the Formlabs Castable Wax Resin, shown in Figure 9. The plan was, following full burnout, to melt aluminum in a separate furnace to 715°C to prepare for pouring. Cast parts would then be removed from the furnace and aluminum immediately poured in to ensure no moisture was able to build on the mold. The mold and aluminum should be at the same temperature at the time of pouring. The parts would then be allowed to cool until solidified before dousing in water and breaking free from the mold.

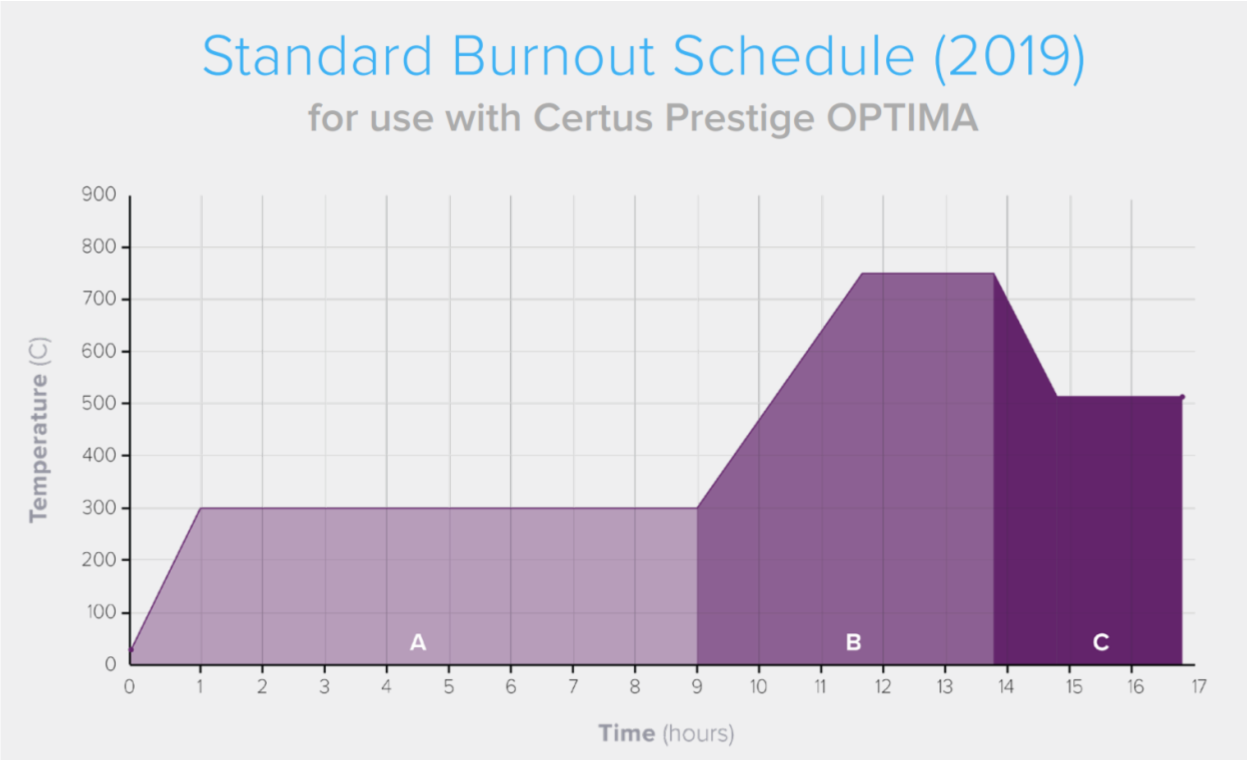


Figure 9: *Standard burnout schedule for Castable Wax Resin, provided by Formlabs.*

Then, after all large chunks of the ceramic shell were removed, a small brush would be used to clean away the remaining ceramic material from the cast part. Once all ceramic was gone, a bandsaw could be used to remove the sprue and runners from the desired part. From there, further finishing steps would be utilized to create or clean up important features.

3 3D Printing Patterns

3.1 Print Setup

Once parts were designed in Fusion 360 with all required features for casting and injection molding, they were sent to the Form 2 printer. A total of 3 prints were made, varying in features, overall volume, and orientation. Analysis of previous prints informed decisions made about print settings for following prints. The initial print followed Formlabs' guidelines for print settings using the Castable Wax Resin. Print 1 was scaled up by 2%, used a layer thickness of 50 microns, and was oriented with the back flat surface parallel to the build platform. Print 2 was scaled up by 5%, also used a layer thickness of 50 microns, and was rotated along one edge so that the flat face was at a 45 degree angle with relation to the build platform. The third and final print was also scaled up by 5%, but used a layer thickness of 25 microns and was rotated 90 degrees to the build platform. Figure 10 shows a comparison of the print layout for prints 1, 2, and 3.

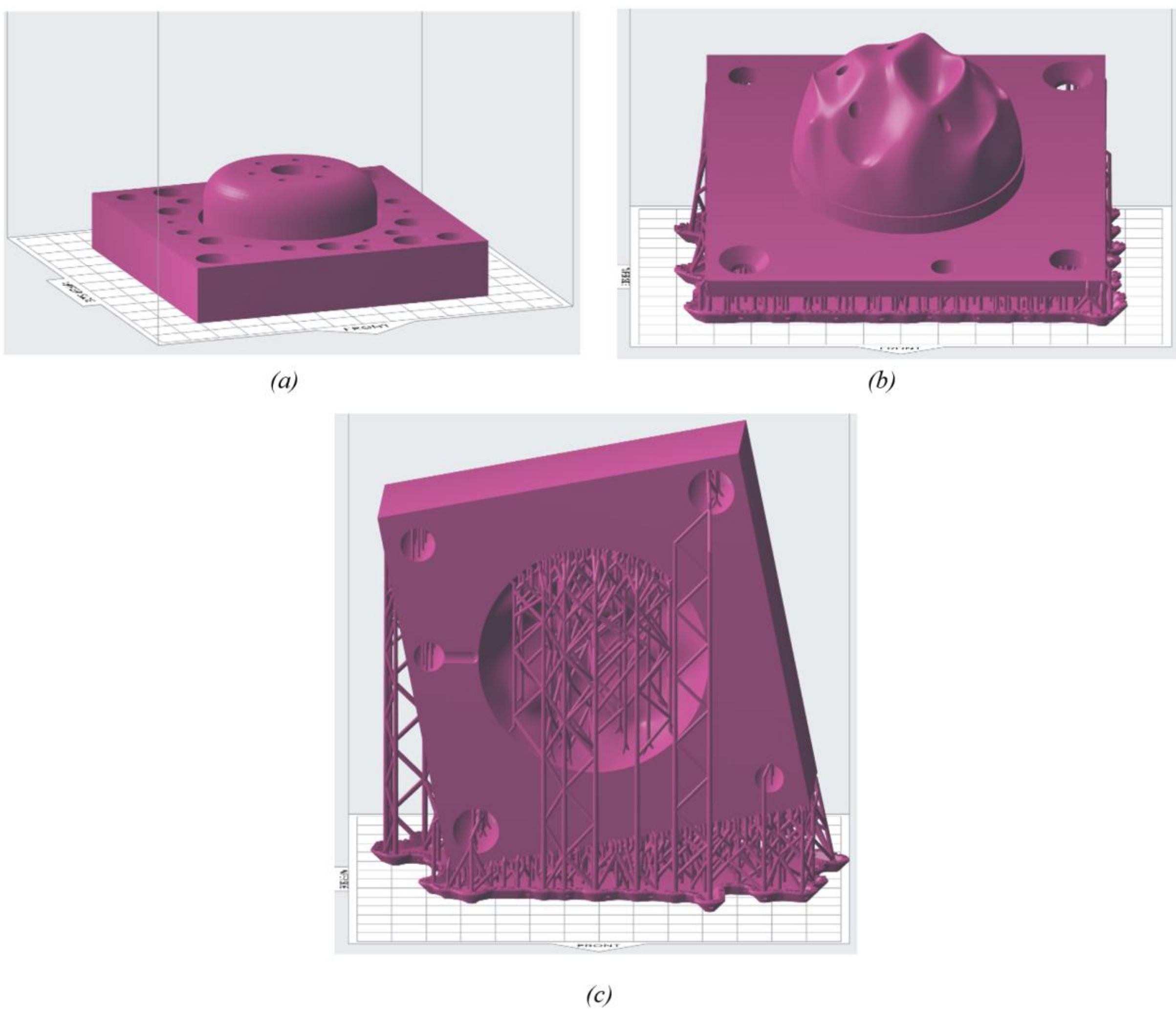
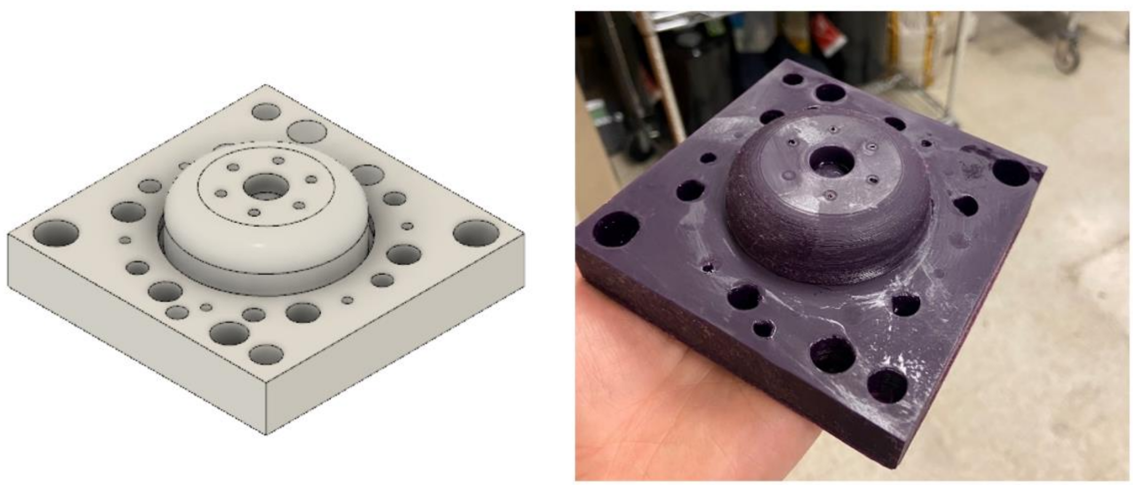


Figure 10: *The computer-generated build layout for parts 1 (a), 2 (b), and 3 (c).*

3.2 Test Part 1

Each print was examined after it was cleaned and all raft support material removed. Measurements of critical dimensions were taken and surface finish of contoured and flat surfaces was evaluated to drive decisions of print settings of the next print. Print 1 took a total of 13 hours and 30 minutes to finish printing, and had a total of 692 layers. The print used 210 mL of resin material. Print 1 was designed with multiple test holes, which were not critical to the function of the part, but served as test features to evaluate the success of printing various hole sizes. Holes were placed in non-critical areas of the part, and varied in diameter from 0.128” to 0.446”. Figure 11 shows a comparison of the CAD model for print 1 and the final printed part from print 1. The final print showed that smaller hole dimensions were not viable, as the only holes that were realized in the print were the largest diameter holes (0.446” diameter), and even these were not fully circular. The final print was also significantly smaller than anticipated, even with scaling up by 2%, per the Formlabs’ specifications. On average, the measured critical dimensions were 7% smaller than specified by the scaled-up CAD model, and were also smaller than the desired final cast part dimensions. The surface finish on the flat faces of print 1 were exceptionally smooth, due to its orientation (the flat faces were parallel to the layer splicing). The contoured surfaces had a slightly rougher finish and the layers were visible to the eye, but the surface finish was ultimately deemed acceptable for the purposes of this study. None of the critical locating or bolt holes were realized in the final print, as they did not extend through the entire part and were not circular. Despite the critical dimensions not being met in print 1, the part was still cast and poured to test other variables in the casting process, and to not waste resin material.

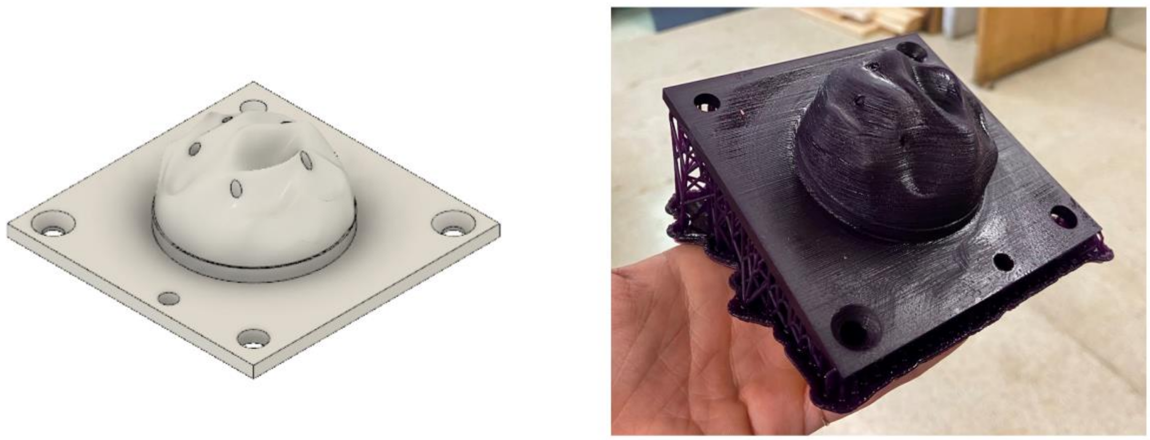


(a) *(b)*

Figure 11: *(a) The CAD model of test part 1, and (b) the final 3D printed test part 1.*

3.3 Test Part 2

Taking these defects and successes from print 1 into consideration, print 2 was set up in the hopes of eliminating some of these issues. In addition, the CAD model for print 2 was designed with more complex contours, in an effort to create a mold that would require significant time to machine. To try to improve the success of small holes, print 2 had the part rotated with respect to the build platform, to allow for better resin drainage. Print 2 was also much thinner in the areas where critical holes were located, which may have improved the quality of them. Figure 12 shows another comparison of the CAD model and final print for the second part. This part was scaled up by 5%, and the actual dimensions were on average a few thousandths smaller than the scaled-up model. Compared with the expected final cast part, though, the features were still oversized. For example, in test part 2, the measured width of the printed part was 4.125", and the desired cast part had a width of 4". This oversizing was intentional, as the part was expected to shrink again during the casting process. Because the part was angled and the layers of the print were not parallel to the flat faces, these faces did see more surface roughness than the flat faces of print 1. Unfortunately, the small, 0.129" ejector pin holes still did not make it into the final print. It is likely that a hole that small, through such a tall boss is not possible to print on this printer with this type of resin. Print 2 took 16 hours and 45 minutes, with a total of 1,303 layers, and used 175 mL of resin material.

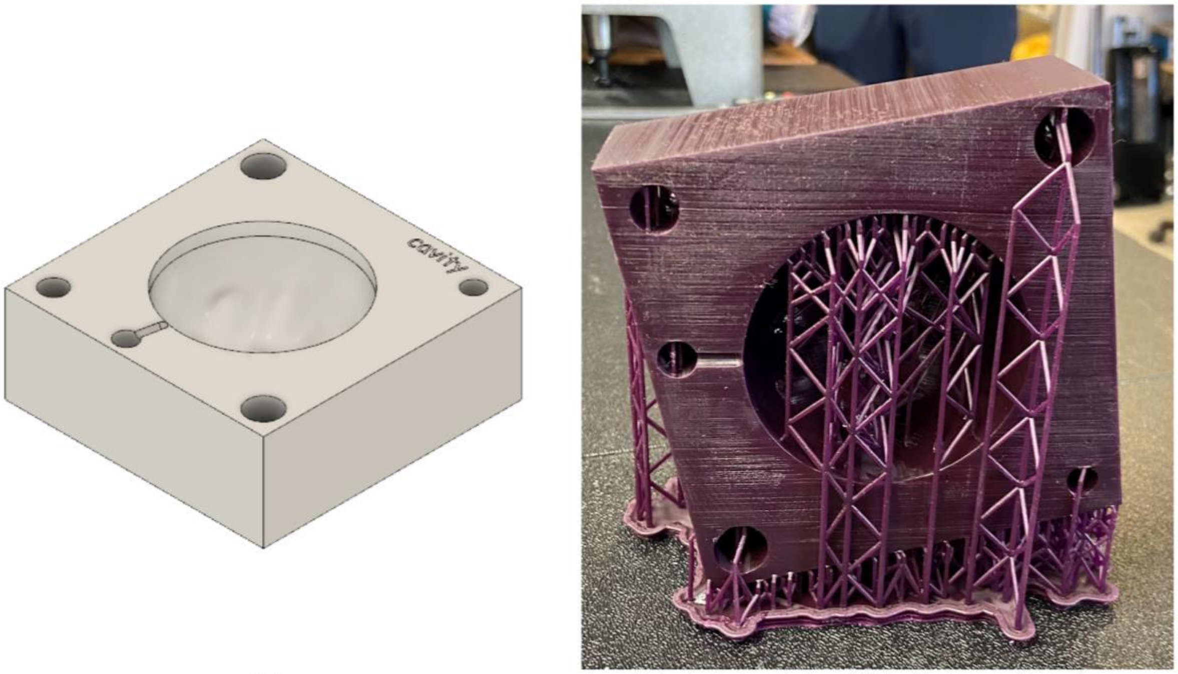


(a) (b)

Figure 12: *(a) The CAD model of test part 2, and (b) the 3D printed version of test part 2 after removal from the build platform.*

3.4 Test Part 3

The third and final print was a matching cavity mold to print 2's core mold. The scaling of part 3 was kept the same as print 2 (5%), so that the two halves would be the same size and fit together as intended. The third print used a 25 micron layer thickness, as opposed to 50 microns used in the first two prints, to test the effects of layer thickness on surface quality and feature size. This print was also oriented nearly perpendicular to the build platform. This orientation was necessary for proper drainage of the part during the print; a less drastic rotation would have created "cups" within the print, where excess resin would likely get stuck and cause the print to fail. Formlabs' PreForm software has built in cup detection to notify the user of potential errors before sending the part to print, which is what detected the presence of a cup for print 3 and allowed the print to be oriented in such a way to minimize risk of failure. Figure 13 shows a comparison of the CAD model vs final part for print 3. Due to the decreased layer thickness and vertical orientation, part 3 had a print time of 2 days 15 hours and 4 minutes, and a total of 5,324 layers. Although this is an exceptionally long print time, the printer could run without interruption and without the need for human supervision, so the predicted labor costs associated with the print were still low. Print 3 used a total of 375 mL of resin material.



(a) (b)

Figure 13: *(a) The CAD model of test part 3, and (b) the 3D printed version of test part 3 after removal from the build platform.*

3.5 3D Print Measurements

Since each part was different, the critical dimensions measured on the print varied between parts. Figures 14 through 16, along with tables 1 through 3 show where critical dimensions were measured, along with their modeled vs. printed values for parts 1, 2, and 3. The tables also show features that were not realized in the prints, as these provided valuable information about the limitations of the 3D printer and resin. Placing parts at an angled orientation to the build platform significantly increased both the likelihood of a successful hole as well as the quality of the hole. Holes through thinner sections were also generally higher quality, as there was less room for variation during the print. Angled orientations also proved to produce better results for overall dimensions, as parts 2 and 3 had uniform scaling across overall height, length, and width, while print 1 saw undersized length and width and oversized height.

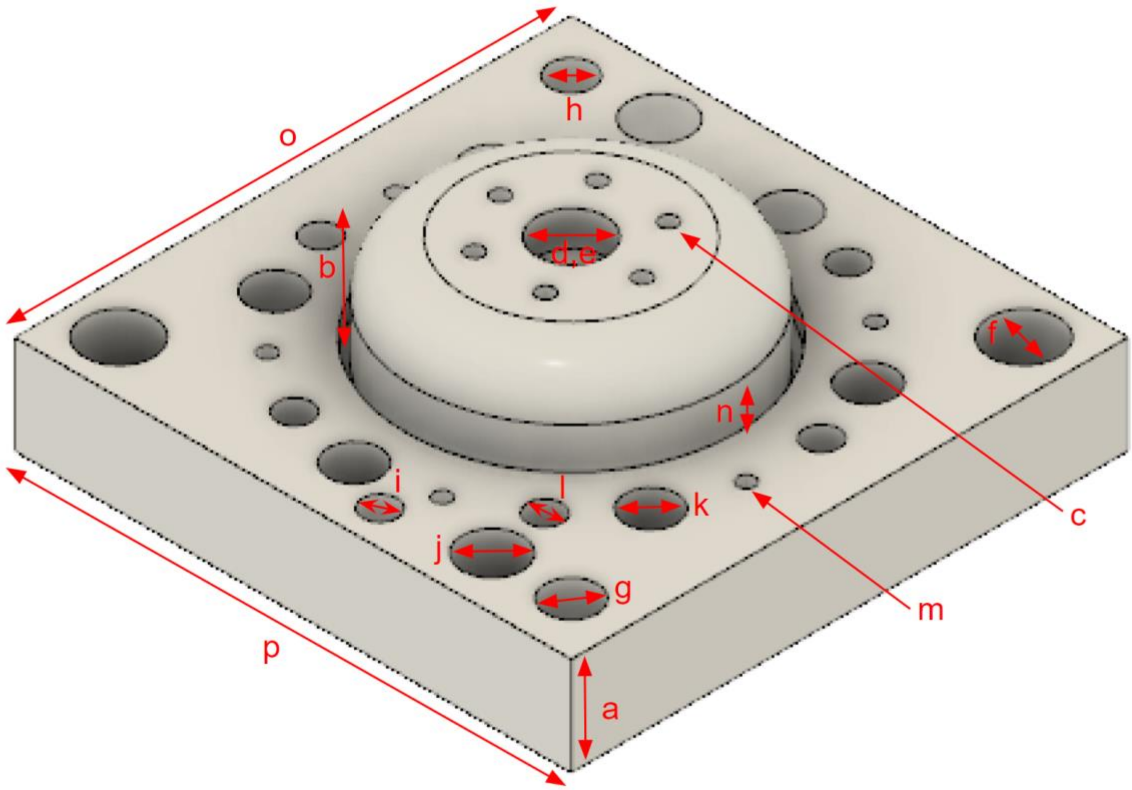


Figure 14: *Labeled critical dimensions for test part 1.*

Dimension	*Model (in)*	*Actual (in)*	*Difference (in)*
a	0.722	0.7795	0.0575
b	0.638	0.5925	-0.0455
c	0.129	Failed	N/A
d	0.51	0.463	-0.047
e	0.255	0.2495	-0.0055
f	0.51	0.4825	-0.0275
g	0.383	0.357	-0.026
h	0.319	0.2825	-0.0365
i	0.255	Failed	N/A
j	0.446	0.4065	-0.0395
k	0.383	Failed	N/A
l	0.255	Failed	N/A
m	0.128	Failed	N/A
n	0.156	Failed	N/A
o		3.895	3.895
p		3.925	3.925

Table 1: *A comparison of modeled vs measured dimensions for test part 1.*

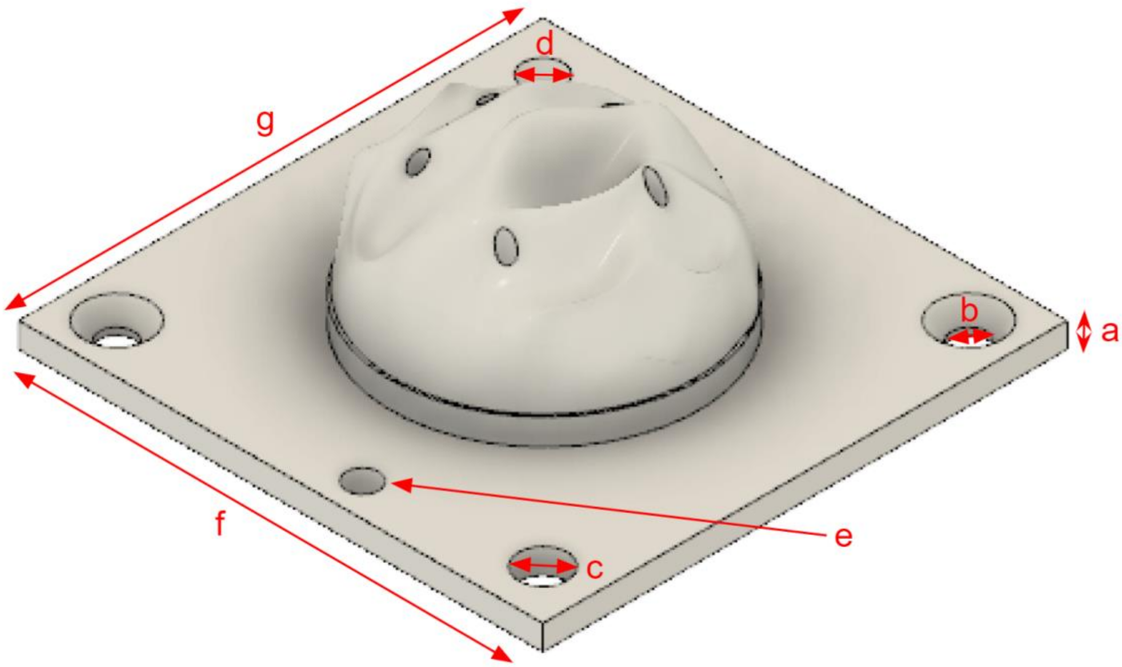


Figure 15: *Labeled critical dimensions for test part 2.*

Dimension	Model (in)	Actual (in)	Difference (in)
a	0.203	0.215	0.012
b	0.279	0.265	-0.014
c	0.394	0.385	-0.009
d	0.328	0.312	-0.016
e	0.263	0.245	-0.018
f	4.2	4.125	-0.075
g	4.2	4.145	-0.055

Table 2: *A comparison of modeled vs measured dimensions for test part 2.*

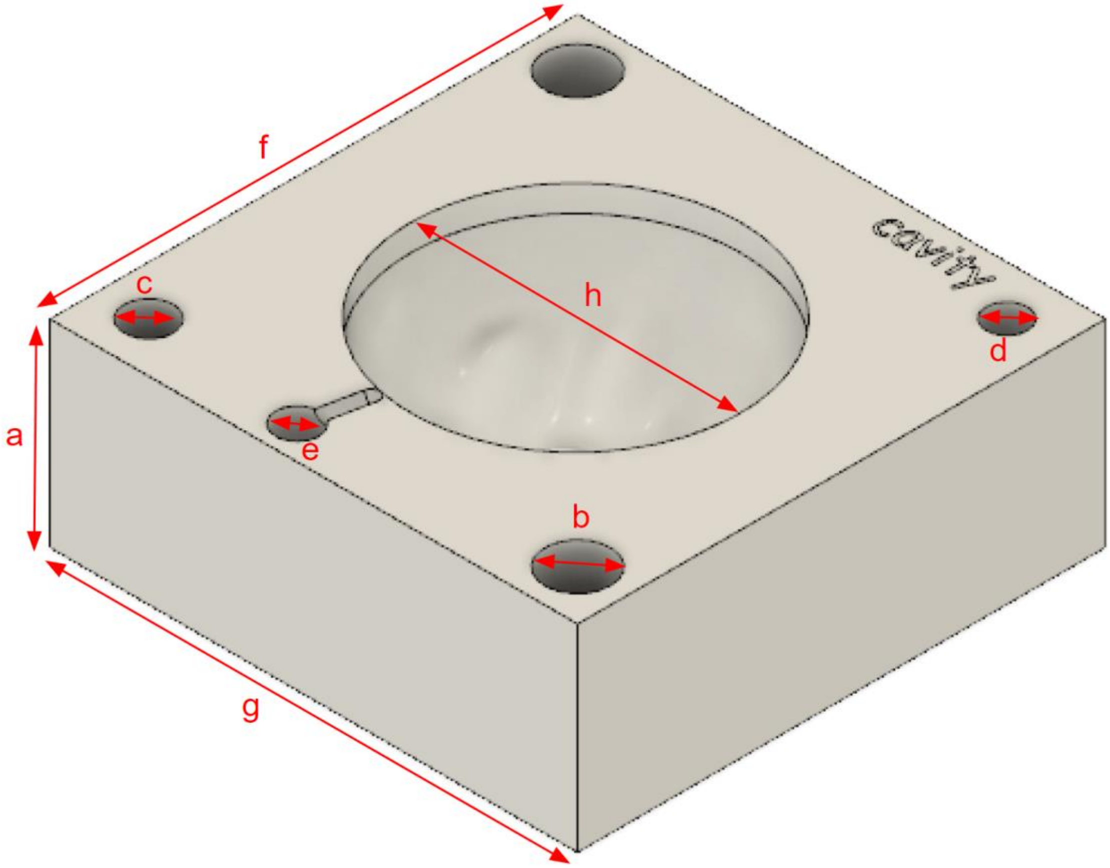


Figure 16: *Labeled critical dimensions for test part 3.*

Dimension	***Model (in)***	***Actual (in)***	***Difference (in)***
a	1.571	1.572	0.001
b	0.524	0.516	-0.008
c	0.393	0.403	0.01
d	0.327	0.306	-0.021
e	0.346	0.325	-0.021
f	4.2	4.185	-0.015
g	4.2	4.168	-0.032
h	2.618	2.612	-0.006

Table 3: *A comparison of modeled vs measured dimensions for test part 3.*

3.6 Part Comparisons

While orienting parts at an angle to the build platform proved to provide more precise feature dimensions, it came with other challenges regarding surface finish and cleanup time. Print 1 saw smooth surface finishes on the large flat planes, as the entire face could be created with one layer. Prints 2 and 3 had clearly visible ridges at the different layers, since each large flat face intersected multiple layers. Aside from this expected decrease in surface quality, the rafts that were necessary to support parts 2 and 3 added unexpected roughness and cleanup time. The rafts were automatically generated by the print software to support overhangs caused by the print orientation. Rafts are cylindrical supports that touch the surface of the part to provide a print surface for material that would otherwise be unsupported. The software designs rafts to be easily removed once the part has finished printing, with little impact on the part itself. For parts 2 and 3, a touchpoint size of 0.80 mm was used for the rafts, a size recommended by the software. Raft density (the number of touchpoints on a surface) was decreased from 100% to 80% between parts 2 and 3, as part 2 required 30 minutes of cleanup time to remove all the rafts. Figure 17 shows surfaces on parts 2 and 3 that were contacting rafts, after all rafts were removed and the part was cleaned. Despite the small touchpoint size, it was not possible to completely remove all indications of rafts and the surface quality of the surfaces contacting rafts was greatly diminished. For part 2, the surfaces contacted by rafts were not surfaces that create the final injection molded part, so the surface defects caused by the rafts were not of much concern. In part 3, however, rafts were placed on a critical surface of the part to provide support for the vertical orientation necessitated for the removal of cups. This surface quality was of importance as it would be directly transferred to the injection molded part, so the existence of rafts in this location was highly undesirable. Unfortunately, even with the decreased density of rafts in print 3, the rafts were still very difficult to remove without further damaging the part, and raft removal still added an extra 25 minutes of cleanup time.

(a) *(b)*

Figure 17: *(a) The large flat face on the back side of print 2 after all raft material was removed. Obvious defects on the flat face are clearly visible. (b) The internal contoured surface of print 3 after all raft material was removed. There were fewer rafts in this area, so defects are not as dense as they were in print 2, but they are still clearly visible.*

Although each of these prints exhibited some type of failure, they were all used for the remainder of the casting process due to material and time constraints. The failures seen on the printed parts were not so catastrophic that useful information could not be obtained from casting them. In an industry setting, multiple test parts would be used to calibrate the printing and casting process, and once these variables were defined, the parts could all use the same settings. Therefore, once all parameters of the process were well understood, the time necessary per part would be drastically reduced.

4 The Casting Process

4.1 Sprue and Runner Setup

After all parts were printed and cleaned successfully, the wax sprue and runners needed to be added to each pattern. A different sprue and runner configuration was chosen for each part, so that the effectiveness of each could be tested. In general, a sprue is a larger diameter wax cylinder that creates the main path for which the liquid metal to flow into, and the runners create smaller channels to spread the flow to different parts of the mold evenly. For the first three test parts, a wax different from the castable wax resin was used to create the sprue and runners, hence the different color that can be seen in Figure 18. Wax rods were melted at the ends using a butane torch, and the melted ends were pressed into the mold at desirable locations. A desirable location would be any non-critical surface of the finished part, typically one of the flat side surfaces.

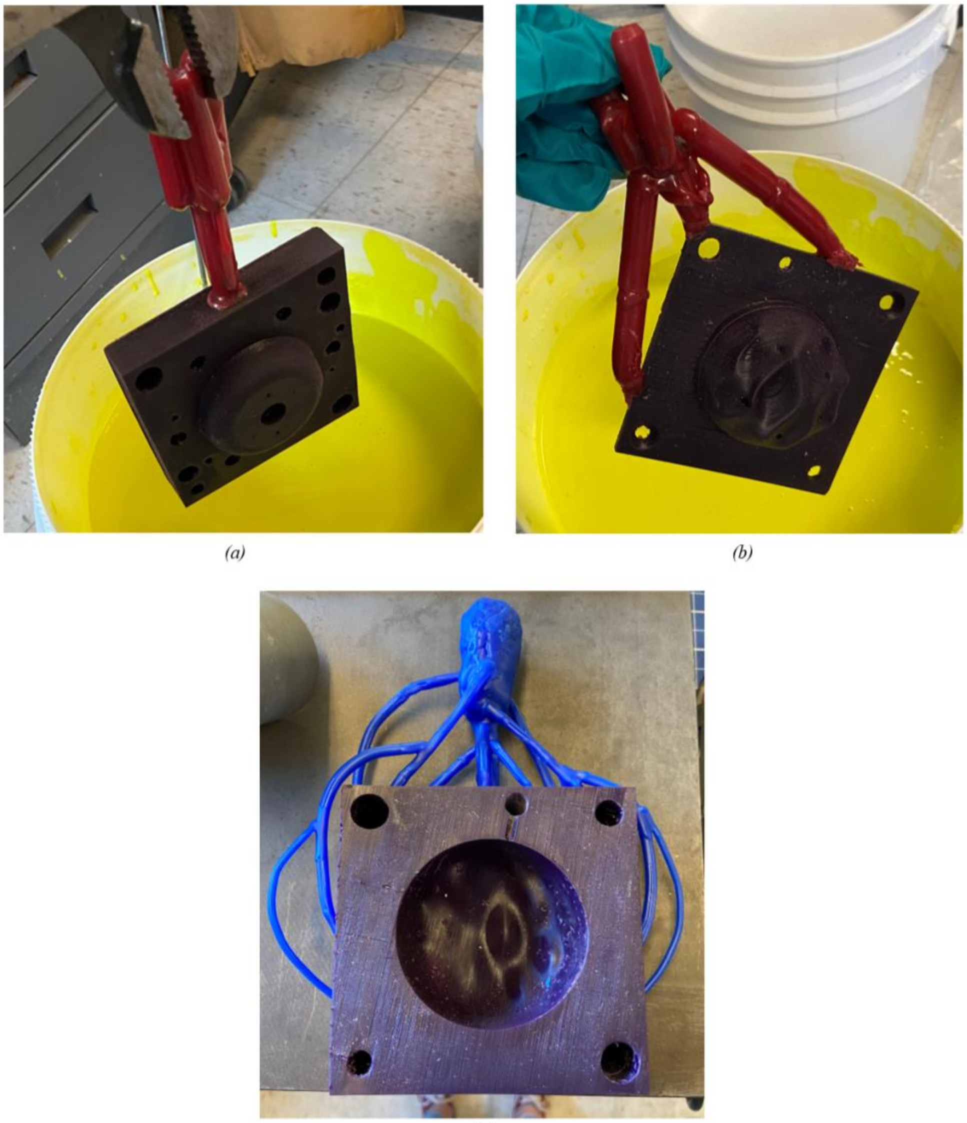


Figure 18: *Each of the three test parts with their wax sprue and runners added.*

Since test part 1 had issues with the 3D printed part mentioned in the previous chapter, it was chosen for the most "risky" sprue configuration. This part used only one sprue connected directly to the part with one runner. This is sometimes preferable, particularly for complex parts with delicate geometries, as multiple runners could potentially damage thin features.

Test part 2 used three runners, ½" in diameter, connected at the top to a sprue made up of three wax cylinders of the same diameter. Part 2 was angled at 45 degrees, so that the three runners intersected the parts at the tip of the square base and at two of the sides. This configuration was chosen to evenly spread the flow of liquid metal to various parts of the mold. Typically, it is desired to have the runners attach to the part near the bottom of the part, to allow the cavity to fill from the bottom up.

Test part 3 used a multitude of thin runners, ranging from 1/16" to ⅛" in diameter. The sprue was a large mass of wax that was softened and formed into a cylindrical shape, roughly 1 inch in diameter. The thin runners all connected at various spots on the part, along 3 of the side walls. Since the runners used here were considerably thinner than the runners used in the other test pieces, a total of 11 runners were used. Having multiple runners also creates more pathways for air to flow out of the mold as metal is poured in, reducing the likelihood of cavity defects in the finished part.

4.2 Ceramic Shell Creation

Once each part had its sprue and runners secured, the dipping process began. Suspendaslurry FS was chosen as the investment shell material because of its versatility and ease of use. Suspendaslurry FS is best used for non-ferrous metals, such as the aluminum used for these injection molding molds. In combination with the slurry material, Ranco-Sil A and B fused silica sands were used in between coats of slurry to build up the ceramic shell.

Following Ransom and Randolph's user instructions for the dipping process, the Suspendaslurry material first needed to be mixed to an acceptable viscosity. During transit and as the slurry sat unused for a few weeks, the material separated into a thin, translucent oily layer on top and a thicker, opaque sedentary layer on the bottom. A mixer attachment in an electric drill was used to stir the slurry for approximately 10 minutes to fully combine the two layers. An acceptable level of mixing was determined through qualitative comparison of the color and viscosity of the slurry with desired qualities found on the Ransom and Randolph site. Though Ransom and Randolph recommends also using a viscosity cup to directly measure the viscosity of the material, one was not available for use, so a qualitative assessment was deemed acceptable for the purposes of this study. The mixing process was repeated each time the slurry was left to sit for at least 24 hours before dipping to ensure uniform layers across all parts.

After the slurry was mixed, each part was dipped in the slurry, then coated in the fused silica sand. For the first coat on each part, Ranco-Sil A was used to coat the slurry, as it is a finer sand that creates a better surface quality. On all remaining coats, Ranco-Sil B, a coarser but more structurally strong sand, was used to create the ceramic shell. Each coat was allowed to dry completely before dipping the following coats. As shown in Figure 19, Suspendaslurry FS is a color-changing material that shifts from a bright yellow to a darker orange when dried.

Figure 19: *A comparison of dry Suspendaslurry material (the orange top half) vs. wet Suspendaslurry material (the yellow bottom half) [16].*

Part 1 was dipped a total of three times (one initial coat followed by two backup coats). For each dip, the part was held with a pair of pliers, dipped into the bucket of slurry, then suspended for a few minutes to allow for excess slurry to drip off and create an even layer. Then, the part was moved to a bucket of fused silica sand, where the sand was poured over the entire mold to form an even layer of sand. The part was then allowed to dry in the bucket of sand. During the second dip of part 1, the sprue (which was held by the pliers) broke free from the rest of the mold, suggesting that the sprue was not fully melted and combined with the runner. For the remaining dips, the part was held by the runner still connected to the 3D printed part as it was dipped and coated with sand.

Figure 20: *The broken sprue of part 1 that fell off while dipping.*

Part 2 used a total of 4 coats, and was also held by a pair of pliers at the sprue. Since this part had multiple runners connecting the sprue to the part, it was more structurally sound, and the sprue survived all 4 coats of dipping. Part 3 was dipped a total of 5 times. Each part was dipped a different amount of times to test the effectiveness of each added coat of slurry. Ransom and Randolph give no guiding advice as to how many coats each part should have. Part 3 was held a bit differently, as the thinner runners were not as strong as the thicker ones used in parts 1 and 2, and because part 3 was considerably heavier. Part 3 was held by a pair of thin pliers in one of the through holes of the part, as shown in Figure 21. The hole that was held was changed each time the part was dipped, to ensure that every hole was coated in slurry material by the end of the dipping process. Figure 22 shows part 2 at the end of the dipping process, after all coats had dried.

Figure 21: *The holding configuration used while dipping part 3.*

Figure 22: *Test part 2 after being dipped and coated 4 times.*

4.3 Wax Burnout

Once all parts were fully coated and ready to be fired, it was time to prepare the furnace. Originally, a custom made furnace for investment casting, from the MIT Nanophotonics and 3D Nanomanufacturing Lab, was to be used for the burnout process. Unfortunately, the furnace had been sitting dormant for too long and was no longer safely operable, even after many hours of attempting to debug it. This furnace was controlled by a raspberry pi, and could be programmed to ramp up and down at very specific intervals. Since this furnace could not be used, a non-programmable furnace in the Pierce Laboratory was chosen instead. This furnace would need to be manually changed to each new setpoint at the desired time, and the ramp up could not be controlled. This would be a deviation from the burnout schedule provided by Formlabs, but was the only viable option within the constraints of this study.

Test part 2 was chosen to be fired first, as it was the part with the highest likelihood of success due to its smaller volume and multiple runner configuration. The part was placed into the oven on a steel drip tray, to catch any wax that might run out of the part and not damage the oven. The oven was already warmed up to at least 150 C when the part was placed inside, and the setpoint set to 300 C, following the provided burnout schedule. The desired ramp up was 4.7 C/min, though the actual ramp up of the oven was around 10 C/min and could not be altered. Immediately after placing the part in the oven, the wax sprue and runners began melting as expected. An unexpected finding was that the wax appeared to be melting through the ceramic shell, which was an initial cause for concern. A few minutes later, large amounts of smoke could be seen flowing into the ventilation duct, so the oven door was opened to reveal the entire part had caught fire. The part was immediately removed from the oven and doused in a nearby bucket of water to put out the flames and remove the hazard. Upon dousing, the sudden temperature drop caused the mold to crack. Figure 23 shows the remains of test part 2 on the wax collection tray.

Figure 23: *The remains of test part 2 after catching fire in the furnace. The ceramic shell was cracked open, revealing the intact 3D printed part still inside.*

4.4 Possible Failure Modes

Though it is unclear exactly why the part caught fire, there are a few reasonable explanations. First, the initial ramp up may have been too fast, so instead of the wax slowly melting out and burning out, it spontaneously combusted into flames and the entire shell caught fire. It may also have been caused by the fact that the oven did not start out at room temperature, so the mold was too quickly heated to 150 C, with no ramp up. The final probable cause of the fire may have been the type of wax used for the sprue and runners. Though it was wax specifically for investment casting, the burnout schedule used was for the Castable Wax Resin material. The wax of the sprue and runners may have required a separate burnout schedule in order to not catch fire, though one was not given by the manufacturer.

4.5 Findings

Despite the shell cracking and becoming unusable, there were a few findings that could still be gathered from the broken model. First, the resulting shell came out very dark in color, nearly black. Other cases of using Suspendaslurry material describe the shell as nearly white once all wax material had been burnt out. The discoloration was almost certainly due to the high amounts of smoke caught in the oven when the part was on fire, and the shell itself could have caught fire as well. Second, the inner 3D printed part had only just begun to burn out and was almost fully intact at the time of dousing, though all the runner and sprue wax had disappeared. This is consistent with Formlabs' specifications for the material, as full burnout should not occur until around 700 C for this resin. Finally, the cracked shell revealed the high quality surface finish on the inside of the mold as seen in Figure 24, suggesting that if the wax had successfully burnt out and metal been poured in, the resulting part would have had the desired high quality surface finish.

Figure 24: *The inside of the cracked ceramic shell of test piece 2. The inner surface almost exactly matched the corresponding surface of the 3D printed part, indicating that the shell would have created a high quality cast part had it survived firing.*

Due to safety concerns, the remaining two parts were not put into the furnace for burnout, since they used the same materials and likely would have caught fire as well. A fourth and final test part was printed, this time with the sprue and runners included in the 3D printed part to test if the wax material used in the first three parts was the cause of the fire. As shown in Figure 25, this part used only the critical feature of the mold (the large extruded contour), to reduce print time and material use. The resulting part could be bolted to a flat piece of aluminum for later use. Unfortunately, it was not possible to redip and fire it within the timeline of this study, so the test of the different material was not completed.

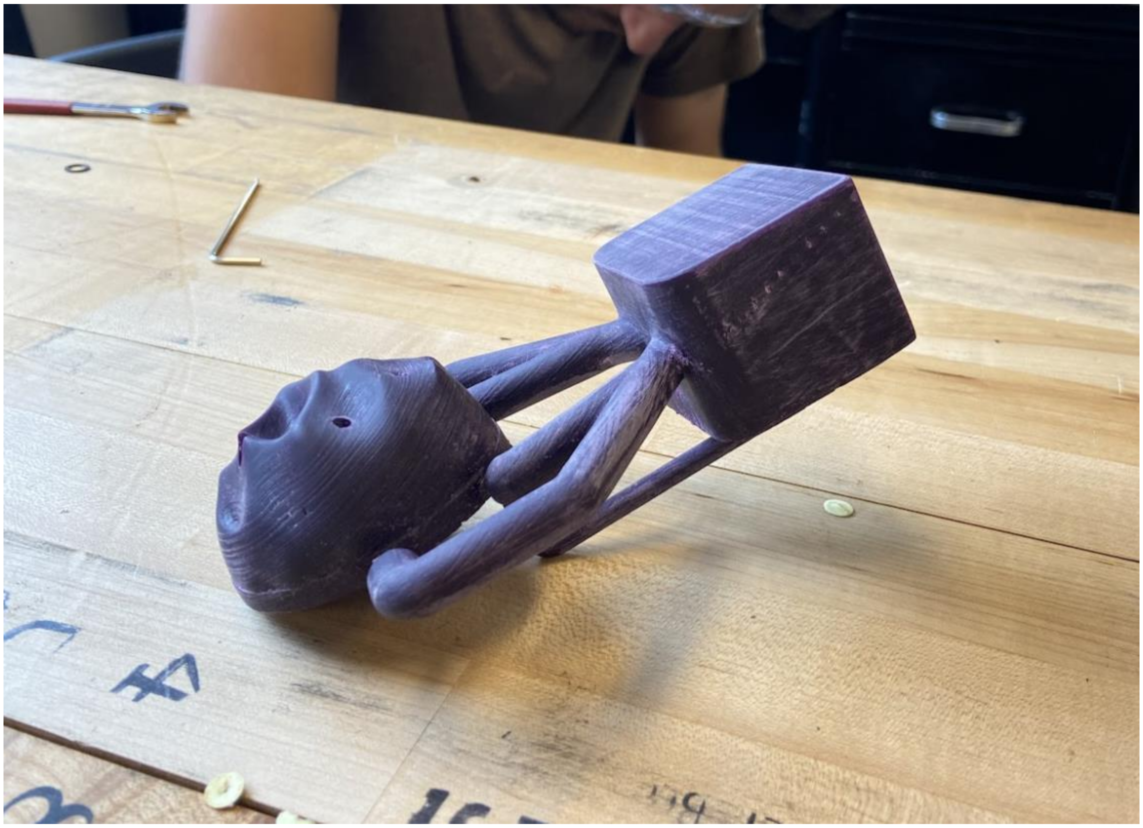


Figure 25: *The fourth test part, with the sprue and runners made of castable wax resin.*

Since no shells were successfully burnt out and cast, the remainder of the study could not be carried out as intended. It was not possible to measure the quality of a machined part against a cast part because there were no completed cast parts. The CAM for the machined parts was created, however, to see how long the machining process would have taken for parts 2 and 3. It took roughly one and a half hours of work to create the CAM setup for the two molds. The Fusion 360 software estimated 2 hours 20 minutes for the machining of part 2, and 3 hours 2 minutes for the machining of part 3. Part 3 would take longer due to the smaller stepover on the finishing passes compared to part 2, since it was desired that part 3 have a better surface finish than part 2 as it would be seen on the outside of the injection molded part.

Though the machining times for both parts were considerably long, they still were significantly shorter than the total amount of hands-on time it took to print, setup, dip, and fire the cast molds. This time difference would have been even greater had the cast parts come out, as additional finishing and post-processing time would have been required to bring the molds to useable quality. Although these findings suggest that it does not save time or money to cast parts as opposed to machining them, the casting process should not be disregarded entirely. Since this study began from scratch, with no prior calibration of the casting process, it is reasonable to assume that the time required for dipping and firing would have been greatly reduced once different parts of the process were calibrated using the resources at hand.

5 Conclusion

Despite the apparent lack of success seen in this study due to limited resources and strict time constraints, there is still reason to believe that investment casting is a viable option for small scale injection mold tooling. Current 3D printers are capable of creating parts of suitable quality, and higher-end printers can do this faster and more reliably than the printers used here. In addition, the dipping process for creating the ceramic shell was shown to be repeatable and also of high quality. There is obvious need for tuning of the burnout process and subsequent metal pouring, but these are both well understood procedures that can easily be parameterized and made reliable.

Though the entirety of this study took many months to complete, in an industry setting with more resources and dedicated engineers, the process could be refined into a robust manufacturing practice. Some potential paths for process improvement could include:

- Quantifying expected shrinkage from 3D printed parts for various geometries and feature sizes.
- Casting only the complex features of a mold, then fixturing that cast part to a pre-made plate with critical locating holes.
- Automating the dipping process by keeping the slurry constantly mixed and utilizing a flow of silica sand to coat the parts.
- Accelerating dry time between coats of slurry using a heater or oven.
- Using highly controllable furnaces with active monitoring of the part to ensure a safe burnout process.

Investment casting is a valuable manufacturing process that can keep up with industry as products become more and more complex. It does require a significant amount of startup time to fine tune various parameters of the process, but once these are quantified, rapid advancements in the utility of investment casting as a large-scale manufacturing process will become apparent.

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