Solid Freeform Fabrication 2019: Proceedings of the 30th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

USING WAX FILAMENT ADDITIVE MANUFACTURING FOR LOW-VOLUME INVESTMENT CASTING

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Abstract

Investment casting is a popular method of converting wax or polymer patterns into metal objects. For low-volumes these patterns can be manufactured using additive manufacturing. However, burning out conventional additive thermoplastics like PLA can be more problematic than removing wax. Often these plastics leave ash residue on the cavity surface, leading to defects in the final metal part. Possible solutions to this problem include using ash-free materials like wax or adjusting parameters to lessen ash buildup. With sufficient consistency in quality, investment casting can be an attractive alternative to metal additive processes. This paper discusses using wax filament on a conventional desktop fused filament fabrication (FFF) additive machine, including discoveries, settings, and design guidelines leading to successful wax prints. The resulting wax filament castings are compared to identical castings produced from colored PLA, and advantages and disadvantages of using wax filament are discussed.

Introduction

Additive manufacturing of metals is still quite expensive in both capital equipment and materials, whether using powder bed fusion, directed energy deposition, binder jetting, or metal/polymer extrusion [1]. One low-cost means of using additive manufacturing to create low-volume metal parts is by printing patterns using a fused filament fabrication (FFF) extrusion system, then using the patterns in lost-pattern investment casting. Hobbyists and small manufacturing businesses will often print their patterns out of the popular FFF materials PLA, ABS, or PETG [2]. However, when the casting is heated to “burn out” the pattern the plastic often leaves behind ash residue that creates imperfections and scarring on the final metal cast part [3]. Despite this problem, investment casting from 3D-printed patterns has great potential for reducing cost in low-volume, high variety manufacturing of metal parts.

Several solutions to this burn out problem exist. By adjusting process parameters, ash build up with these materials can be lessened to a certain extent. Additive manufacturing processes can also print with wax and wax-like materials that burn out more cleanly [4]. Wax printing has been demonstrated with multijet printing [5], selective laser sintering (SLS) can use clean-burning styrene [6], and resins for stereolithography (SLA) are marketed as “wax-like” [7]. However, these processes are typically higher cost and difficulty than desktop FFF. This paper will discuss the viability of using a relatively new wax filament on a conventional desktop FFF

3D printer, including discoveries, settings, and design guidelines leading to successful wax prints. A comparison is also shown between castings made from identical wax and PLA prints.

Working with such a new material and with such little experience or knowledge about the material within the 3D printing community proved to be difficult. In order to have a proper understanding of how this material was different from other printing materials, it was deemed necessary to conduct a series of experiments by creating patterns to find a starting line. Other sources of information regarding this technique for this material were rare and provided mostly base settings similar to what the manufacturer provided. For this reason, a design of experiments was initiated to determine the most important settings, and finally some initial tuning after concluding the DOE. The research of this paper was conducted consistently with a Prusa i3 MK2.5 using a .4mm nozzle, .2-layer height, and the 1.75mm wax filament purchased from Machinable Wax. Machinable Wax produces their products in house and perform their own tests to determine material properties. Table 1 shows the material properties supplied by the manufacturer. As an added measure of consistency, the printer was enclosed at all times by a Plexiglas enclosure.

Initial Testing

The very first tests conducted with the material were basic calibration tests to see if the material could be used for printed patterns. The filament settings used initially were standard Prusa PLA settings set to 180 C, a bed temperature of 90 C, and nothing else differing. Initial tests were as basic as printed rectangles, printing vertically with no closed top. Before discovering that Prusa has protective coding to halt all extruder movements below 180 C, a design of experiments was done to determine how to produce the best cube. The information regarding the settings such as controls and variable can be found in Table 2. The test results concluded that temperature had the largest influence on how a print would turn out, whether it would be straight, or sagging and sloppy. It was shown by measuring cubic volume and straightness of edges that lower temperatures performed better.

Table 1. Material properties of Machinable Wax Filament [8]

Hardness:	50 (Shore "D" Scale)
Specific Gravity:	0.92
Specific Density:	0.91238 grams / cubic cm
Flash Point (COC):	575 degrees F
Melt Point (Ring & Ball Method):	242 degrees F (117C)
Viscosity 270 degrees F:	34,400cP
Volumetric Shrinkage:	5% typical
Ash content for lost wax casting applications:	low (.004%)
Coefficient of Thermal Expansion (in./in. °F):	9.5 x 10-5
Coloring:	blue dye, permanent, oil base

Table 2. Print settings for test objects

Print Settings Table		
Settings	**Initial**	**DOE**
Variable		
A-	180 C	See Table 2
B-Cooling	10%	See Table 2
C-	2 shells	See Table 2
Controlled		
Temp (Bed)	90 C	90 C
# of Shells (Top)	5 Shells	5 Shells
# of Shells (Bottom)	3 Shells	3 Shells
Retraction %	0 %	0 %
Infill %	0%	0%
Cooling fan %	See below	See below
-Layers 0-10	0 %	0 %
-Layers 11+	10 %	10 %
-Layers 11+	10 %	10 %

Table 3. Values referred to in Table 2

	Low Level (-)	High Level (+)
A-Cooling	5%	10%
B-Print Speed (Perimeter)	20 mm/sec	70 mm/sec
C-Pause Time	0 sec	5 sec

Once better print settings had been determined from the DOE, the printer's firmware was updated to remove a low temperature limit, allowing lower hot end temperatures. For further testing, a closed top pyramid was chosen to see if the wax would be capable of closing a hole and building gradually inward without supporting fill. By keeping the temperature lower and increasing the fan speed dramatically, print quality improved and became more consistent. As shown in Figure 1, the prints became better with increased fan speed, eventually reaching a fan speed of 100%. These prints became good enough and similar enough to be considered comparable to a PLA print.

Final pyramids were printed with the settings of the DOE apart from 100% fan and a printing temperature of 145 C. These prints proved to be the best prints yet and are the three far right pyramids in Figure 1. As it is common within the 3D printing community to produce and use prints to gauge where improvements within the settings of a printer or individual print need to be made, and seeing that the settings were well enough off to have minimal error, it was time to print an actual object.

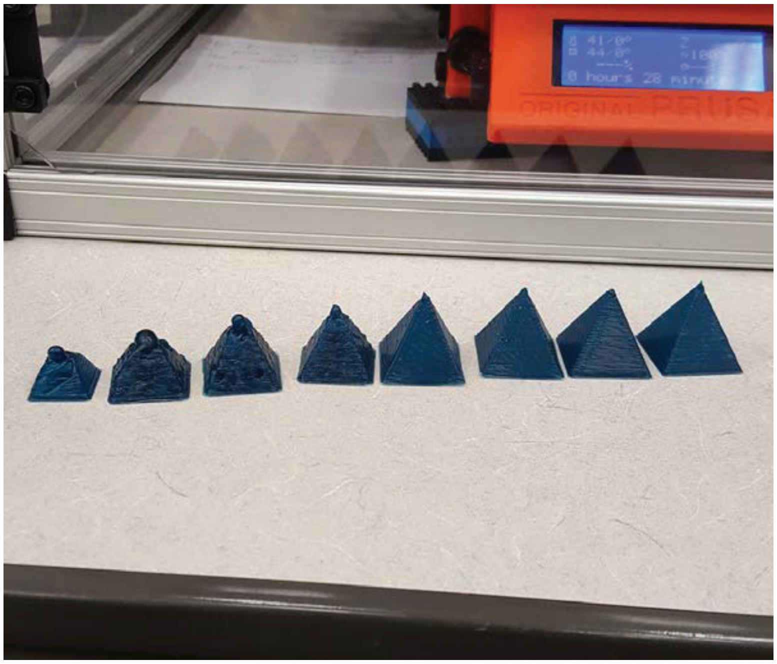

Figure 1. Pyramid Test Series

Bridging, Overhanging, and Stringing Testing

The first test object was a simple benchmark boat. Although simple for most printers and usually quite easy to print, this seemed to be quite a difficult task for the filament, even with a new sweet spot temperature of 140 (140-150 manufacturer recommended). Theoretically there should have been no issues with the bottom of the boat, but it would be the top of the boat that would test retraction, bridging, and printing small surface areas and details. This too did prove to be a problem, but the bottom developed two new issues which were linked to cooling. Because this was a larger print than the cubes or pyramids, and because of fill, the greatest enemy to the print was warping. Wax is not known for retaining heat, as was discovered in Figure 2. All prints in Figure 2 detached from the bed after significant warping with or without horrible layer separation. In order to try and keep the wax from cooling too quickly, the cooling fan was turned off for the first 5 layers, and then the first 10 layers. The skirt was also enlarged dramatically from about 1 or 2mm to about 8mm. The benchmark print took longer to complete one layer or one perimeter than the cubes or pyramids, and the gooey wax had enough time to cool without assistance from the fan by the time the nozzle came around for another pass. In Figure 2 the closest boat on the left was printed without fill while the rest of them were. From bottom to top the fan speed was decreased down to about 15-25% and less. To prevent separation from the bed, hair spray was used to provide further adhesion and grip to the stock removable bed provided by the Prusa upgrade kit.

On the right of Figure 2 is the first successful print using wax that was not a basic shape. Although quite a poor example of a benchmark boat, it was quite a significant achievement after dozens of hours playing with settings and experimenting. This boat was printed using the settings previously discussed. As can be seen, it struggled with retraction stringing, printing the walls for the cabin, and printing the smoke stack. Unexpectedly, it did bridge the roof, although looking under the roof it initially did struggle greatly within the first few layers. It did, however, do a reasonably good job printing the boat hull with a considerably smooth finish.

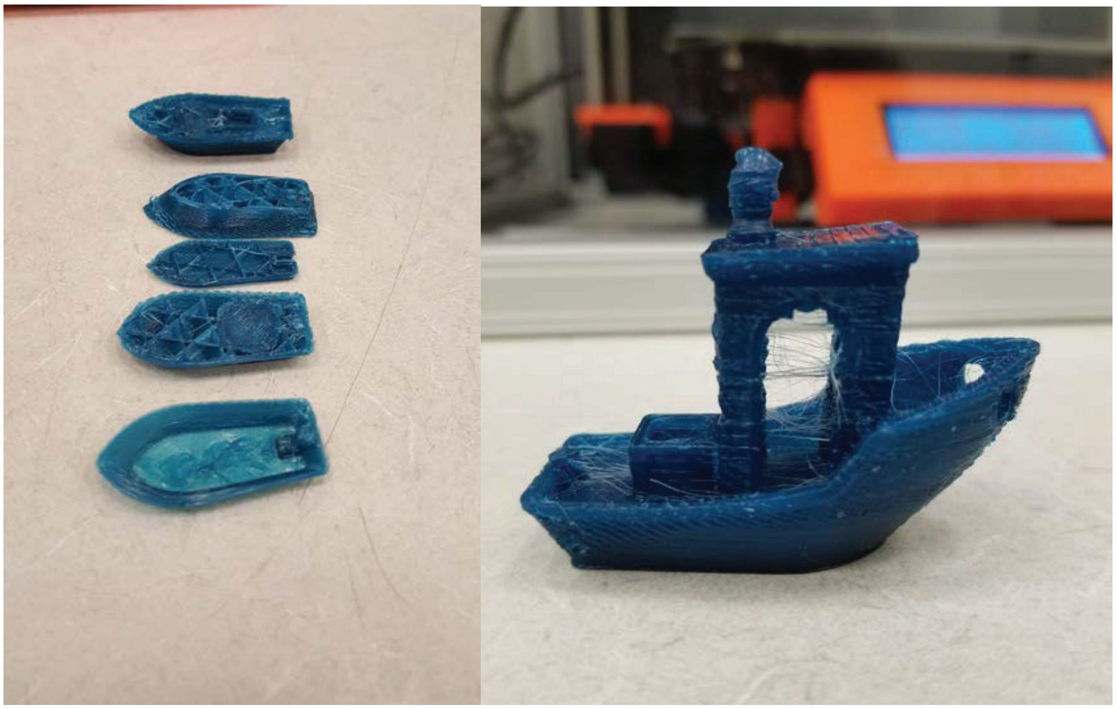

Figure 2. Benchmark Boat Test Series

Finally, there was a print that had been completed without failing as so many before had previously done. The hairspray was more effective with keeping the print attached but more refining needed to be done on the settings. To take a closer look at what it did well, a new and simple pattern was chosen to put the material to the test. The pieces printed were from a folder of user-created parts on Thingiverse.com for a Y-Axis belt tensioner on an Anet A8. The two pieces were the plate and the lead screw. To date, these pieces are among some of the best prints obtained from this finicky material but were not used to make a casting. Amazingly, these two prints fit together perfectly without error or grinding threads. The overall finish was quite smooth, so a twin set was printed using PLA to compare the two side-by-side. Naturally the PLA set screwed in smoother and had an overall better appearance, but the wax was not far behind. The only noticeable difference between the two sets of prints was that the PLA had captured a little more detail around the grips of the screw, giving it more of the original intended shape. Following these tests, it was significant that this material was able to produce threads and was able to print simple piece prints at a near flawless level. The example can be seen here in Figure 3.

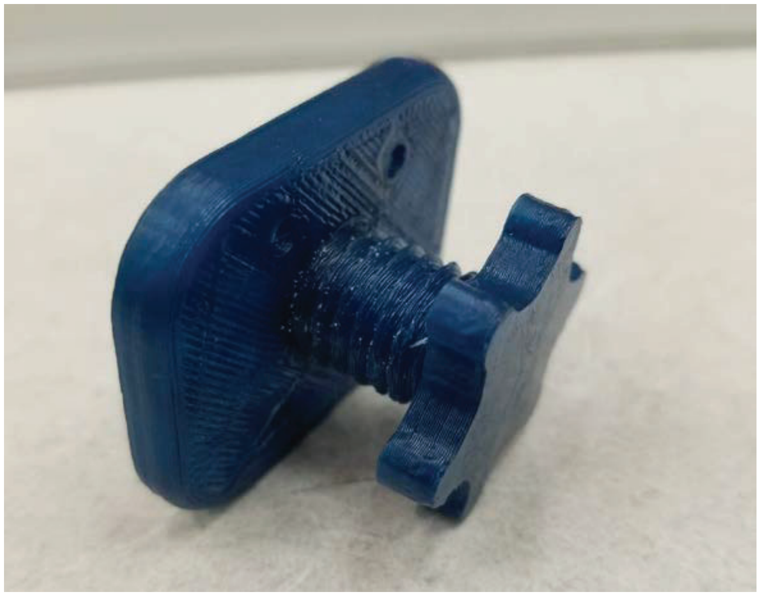
Figure 3. Lead screw test object

Although it had been established that the wax could produce a simple print within reasonable quality, it was yet to be determined how complex of a pattern could be achieved. With this in mind, a basic chess piece was selected to be printed with the pattern again coming from Thingiverse.com. Unlike other chess pieces, is did not have any dramatic overhangs or bridging that would need to be performed by the machine. At about 1.5 inches tall, the first chess piece was a success in the idea that it did not fail during printing. The downfall of this print just like the benchmark boat's smoke stack was a small detail at the top of the chess piece signifying it was a king. During the print it was noted that the layers were being completed quickly, not leaving much time for cooling. The cooling fan was manually increased to 100% at the end of these prints which did not work and consequently caused a slight layer separation. It was also noted that because the area being printed on was so small, the hot end was not allowing a necessary amount of time for cooling which caused melting of the freshly laid wax causing clumps and additional hiccups.

To try and give the chess piece more time to cool per layer while not being immediately available to tend to the machine, a second chess piece was programmed into the G Code in hopes of allowing a layer to get time away from the hot end. This method did prove to be effective for helping some areas of the print, but ultimately the small parts of the print proved to be worse off because of the excessive stringing and clumping. Unlike PLA, the wax is difficult to clean up without damaging what lies beneath the stringing. Figure 4 shows the high level of stringing affecting the print quality. With this as a prime example, the concept of using a second print or sacrificial pillar would have to be postponed until the stringing could be resolved. In order to tackle the problem, slicer settings in the extruder motor were altered to increase the speed of retraction as well as the distance of retraction. A few examples of the tests can be seen in Figure 5. Early tests suffered greatly from the posts breaking mid print since there was often no consistent shape to them. Tests pictured from left to right had the settings increase from standard settings to 3mm of retraction at 100mm/s with varying high levels of fan. Although these changes did help, they were never consistent in what they would produce. It should be noted that these retraction settings were never tested using considerably large prints, however these retraction settings were used for a larger square-shaped print.

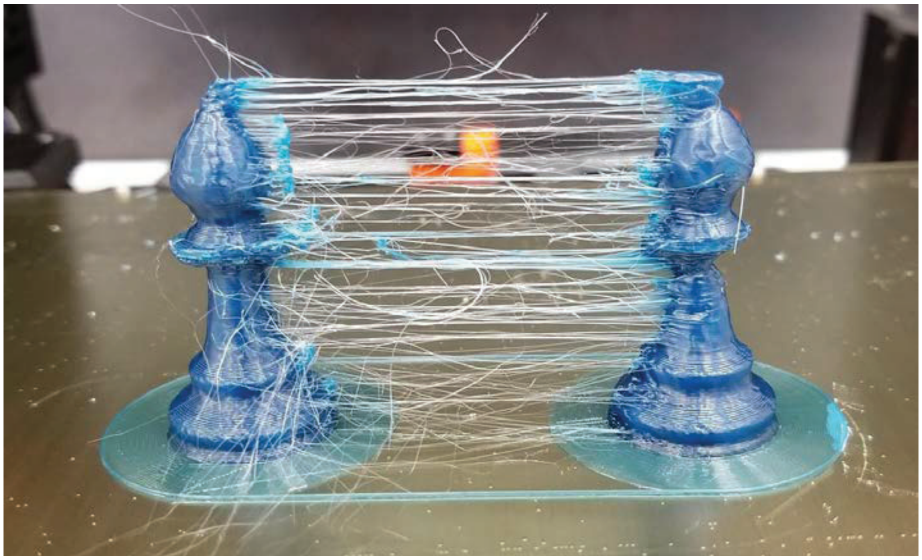

Figure 4. Stringing on chess piece test object

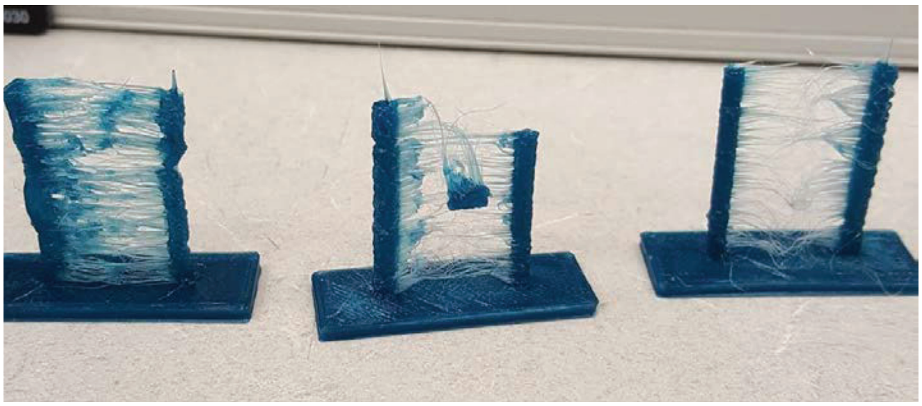

Figure 5. Retraction testing

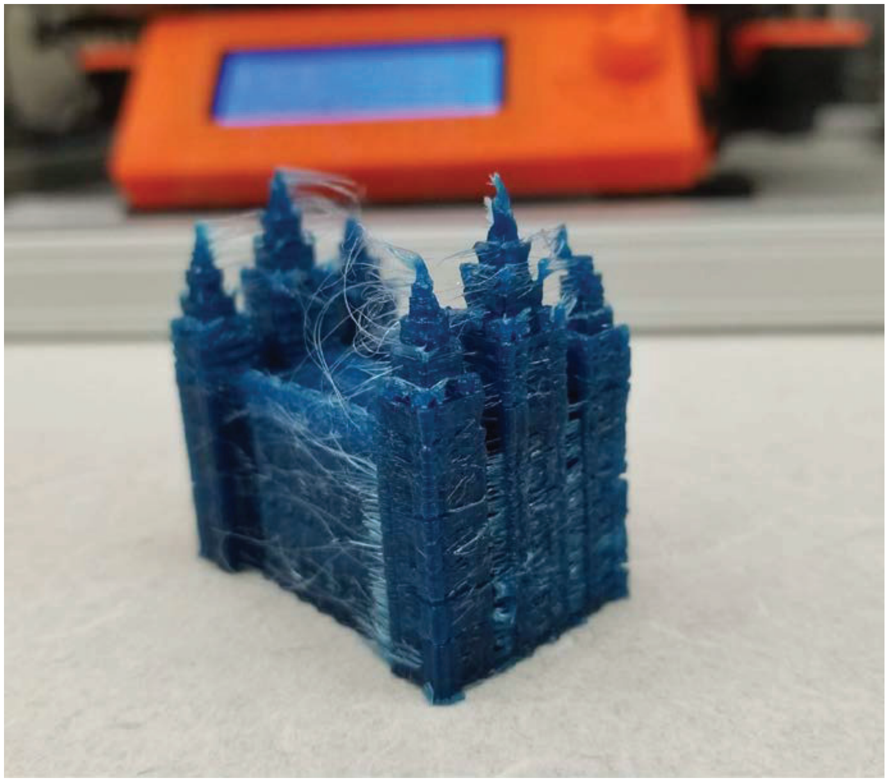

Figure 6. Complex test object

The largest print created while using retraction settings was a building structure an inch and a quarter long and can be seen in Figure 7. This print had tall spires, one on each corner, but the main shape of the building was a square. The stringing in this instance was much lighter and almost fluffy compared to the two chess pieces. The print did finish, and some features and details managed to come out, but the extra wax left behind proved to be too much to clean up, even with a heated shaping tool. The part also exhibited extreme warp and separation of layers. Ultimately, retraction was turned off and abandoned. Prints discussed and shown later in this paper will show the results of turning retraction off.

All testing thus far indicated that small details are in most cases not suitable for this material. Many printer settings as well as filament settings were changed and tested on a range of values. Small prints in general usually produced more problems, and it seems plausible that the wider and longer a print was, the more successful and comparable to PLA the prints would be. While producing larger prints, the printer and filament settings remained virtually the same.

Investment Cast Testing

With still much potential despite earlier failures and being unable to determine settings that would achieve the desired results, larger prints were selected for testing in hopes of creating a proper casting. There were several conditions that had to be met for a file to be considered for printing: The print had to have a flat bottom or flat spot to support a riser, it had to have no dramatic or large overhangs, it could not have small details, and it could not have parts of the print that would produce stringing, and it could not be skinny and come to a point. A publicly available model of an Easter Island statue was chosen for this test. The settings thus far discussed were used, and after producing three acceptable prints with minor layer separation issues, steps were taken to reduce the fan percentage, increase the number of layers without the cooling fan, and increase the skirt size to about 7 mm which produced near perfect prints, an example of this print can be seen in Figure 7. The heated sculpting tool was needed, however, as the top of the head had small gaps that needed filling from sloppy final layers. It also needed a small amount of cleanup on the chin from a little too much overhang. Other zits or blobs were small enough to be removed with a fingernail and caused no damage or marring to the surface.

Figure 7. Easter Island test object

As there was now a print that was high enough quality to hold side by side with a PLA copy, what now needed to be known was how well this material would hold up in a casting. A small paper cup was attached to the bottom (printed wax sprue attached for later print) of the print, and a ceramic slurry was used to coat the prints after being etched and rinsed in a mild citric acid. The same process was used later for the PLA print. After dipping the pattern in slurry and fine grain ceramic sand, the pattern was allowed to dry for at least 4 hours before being coated in the next layer. This process consisted of 3 layers of fine grain and 4 layers of coarse grain sand. Once both patterns were finished drying, they were both placed in a gas furnace where the wax and PLA was melted out of the ceramic shells. The temperature used to initially melt the materials was 450 C for 90 minutes and then raised to 1200 C for 10 minutes to reduce the chance of shocking the shells with a large temperature difference between itself and the molten material. For cost and simplicity, scrap aluminum was chosen to be the casting material. When the oven was opened the shells were quickly looked at and analyzed. Both seemed clear of ash, but the PLA print had yellow stains left behind by the PLA and the wax shell had developed a crack but was still structurally sound. These observations can be noticed in Figure 8. The aluminum was then poured, and the castings were allowed to cool for about 20 minutes. The wax was broken open first and the PLA was broken open second having around 5 extra minutes to cool. Immediately the crack was visible on the wax casting as well as a rougher finish. But, the casting itself was quite good with no other defects. These defects were mostly caused by the crack in the ceramic, and the rougher surface potentially because of the shorter amount of time given to cool. The PLA, on the other hand was next to flawless. Besides having some slight ash left over on the surface of the top of the head, there were no noticeable flaws. Side by side, the PLA was a clear winner not because it was flawless, but because the details like layer lines and edges were sharper and much more defined. Figure 9 compares them side by side.

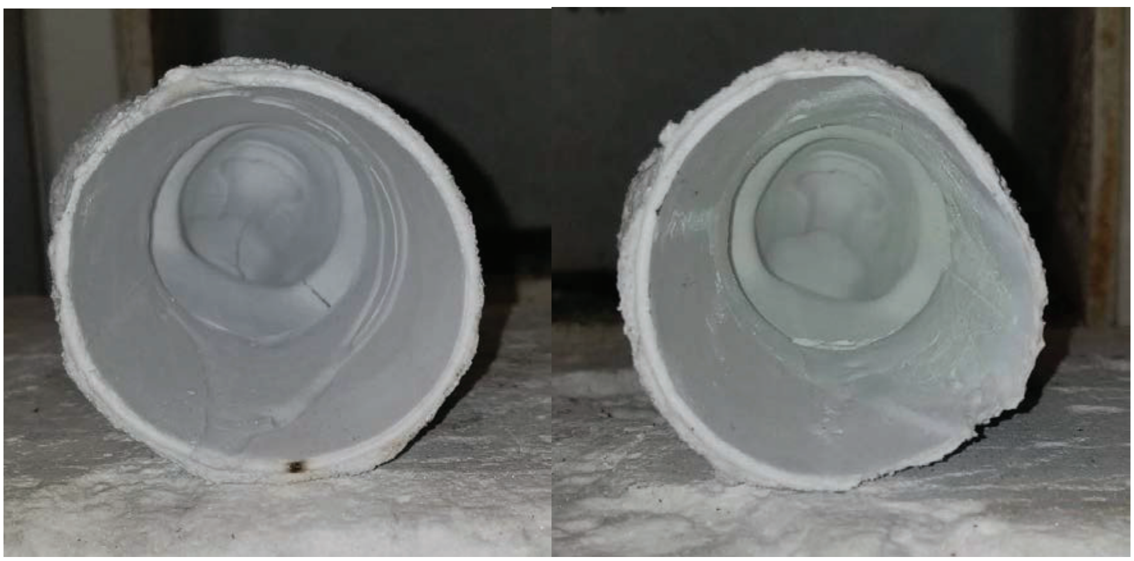

Figure 8. Investment casting molds after burn out (left: wax; right: PLA)

Figure 9. Final castings (left: aluminum from wax; right: aluminum from PLA)

Once cleaned up with a brush and having the sprue removed, the wax casting was compared with a wax print shown in Figure 10. Ultimately the casting was true to the shape of the original with very little variation. However, the casting was not significantly better than the casting from PLA. After testing several other shapes and continuing to experience bed adhesion problems, warping, layer separation, melting of top layers, and poor replication of small details the decision was made that overall, PLA is still a better option in most cases.

Figure 10. Detail of wax pattern and resulting casting

Conclusion

In conclusion, the settings discussed in this paper were able to provide the best prints for research without the use of polishing to improve the shapes or surfaces. For the best results, patterns were produced using a hot-end temperature of 140 C, a bed temperature of 90 C, a fan delay of about 10 layers and then running at 15-25%, low levels of infill, and 3-5 shells. It was found through these experiments that the wax provides an extremely clean burnout, but at the cost of hours of playing with settings for one pattern. The greatest difficulties of working with this material were melting layers, layer separation, bed adhesion, stringing, and printing of small parts. We recommend that this process be used when larger prints with lower amounts of detail, minimal overhang, and low-level volume are primary factors. When this is the case and tolerances and edges are not the end goal, the wax filament provides an extremely clean and accurate portrayal of the original CAD design, and a very clean casting. For the time being this specific wax is not a promising alternative to PLA for hobbyists but has the potential to show promise for individuals or companies seeking a flawless burnout. Additionally, with the advancement of this and other filaments in the future as well as the refinement of printer and filament properties, this process has the potential to show great results for low-volume investment castings.

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