Evaluation of a Low-Cost Material Extrusion Printer for Investment Casting Applications

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Background

It is nearly 30 years since the QuickCast build style was introduced by 3D Systems for use in investment casting. Since that time, much has happened.

- Several new technologies for printing investment casting patterns have been introduced.
- The use of printed patterns to create prototype investment castings has become standard in the industry.
- Printed patterns are now commonly used for very low volume investment casting applications, an application that had been out of reach for investment casting in the past due to the cost of tooling.
- Printed patterns have enabled investment casting to manufacture complex geometries that cannot be molded.

Because printed investment casting patterns are an intermediate step in the manufacturing process rather than the final product, they do not get the exposure that some other applications get. However, it can be argued that in terms of acceptance and number of uses per year, printed patterns is one of the most successful additive manufacturing applications.

Four technologies dominate the creation of printed patterns for investment casting. They include:

- **QuickCast** – This is a hollow build style for stereolithography with an internal hexagonal structure. It is the oldest pattern printing technology and the most widely used in North America. The most popular printer for QuickCast is the ProEx 800 system from 3D Systems.

- **CastForm** – Castform is a selective laser sintering process using polystyrene powder. It has lost favor over the last several years but is still used heavily by a few foundries. The most common printer used for Castform is the s60 system from 3D Systems.

- **Printed Wax** – an inkjet printing process can be used to print wax patterns. This is the only process that creates patterns in an actual wax material. The most common printer used for printed wax is the ProJet 3600 series printers from 3D Systems.

- **Voxeljet** – Voxeljet, a German manufacturer of AM systems developed a binder jetting process using PMMA (polymethylmethacrylate) powder. It is the newest of the most popular printers and has gained favor in several casting applications.

These four pattern printing technologies account for more than 98% of printed patterns used in North America. In 2016 I did a detailed comparison of these four printing technologies and will use data from that study later in this paper.

New printed pattern technology

A few years ago, while touring investment foundries in Asia, I began to hear of low-cost material extrusion printers being used to print prototype investment casting patterns. Material extrusion printers typically use a filament of material which is heated to melting at the print head and then extruded out onto the workpiece. This printing process is also known as Fused Deposition Modeling (FDM), a term introduced by Stratasys, one of the major 3D printer manufacturers.

I believed that these low-cost systems had limited accuracy, produced rougher surfaces, and were slow in comparison to the more popular systems. I doubted that they could effectively compete with the systems listed above.

Last year, I was approached by one manufacturer of low-cost material extrusion printers and asked to evaluate their system for pattern printing applications. The system to be evaluated was an Ultimaker s5 printer running the Polycast filament from Polymaker.

The Ultimaker printer is what might be classified as a low-end industrial printer. It is much more expensive than home printers but is much less expensive than the printers more commonly used in industry such as those mentioned above. There are several similar printers on the market.

The Polycast filament is a PLA based material and was developed specifically for investment casting applications. One advantage it has compared to more commonly used PLA filaments is that it is vapor polishable.

Evaluation Criteria

What is important in evaluating such a system? The criteria I used in my 2016 study was based on concerns that several foundries had expressed to me over the years. Those criteria were:

- **Build Envelope** – The build envelope is the length, width and height of the build space of the printer. It defines the largest part that can be built by the printer. Foundries want to know if most of the castings they normally build could be built in one piece by that printer.
- **Accuracy** – Clearly, the casting can be no more accurate than the pattern it starts with. Consequently, the accuracy of the patterns is especially important to a foundry. At the minimum, it must be within the tolerances claimed for the casting it will produce.
- **Surface Finish** – The surface finish of the casting can be no better than the surface finish of the pattern it comes from and most likely will be worse. For some casting applications, surface roughness is an important acceptance criterion.

- **Build Speed** – For prototype applications build speed is not as critical as it would be for production, but the printer must be fast enough to deliver patterns in time to meet customer delivery expectations.
- **Printer Cost** – The cost of the printer is important, especially considering that for most foundries prototype and very low volume orders account for less than ten percent of their revenues. They cannot justify large investments in a technology that will affect only a small part of their revenues.
- **Pattern Cost** – Just as important as printer cost is the cost of the patterns produced by the printer. If the pattern cost is too high, it simply will not make sense to use printed patterns instead of molded wax patterns.
- **Ease of Casting** – Difficulty in casting printed patterns has been the largest roadblock to greater usage. For most pattern printing processes, creating an acceptable casting requires significant variations from the process used for molded wax patterns. Those variations increase the cost and complexity of casting and are a disruption to the foundry. Consequently, ease of casting is an important consideration.

The first four of the above criteria are measures of the printer performance. The next two are measures of operating cost. The final criterion is a measure of casting performance.

Evaluation Process

To evaluate the system, Ultimaker provided two s5 printers to Wisconsin Precision Casting Corporation (WPCC), a leading user and proponent of printed patterns. WPCC used the systems for creating prototype patterns for a period of over three months for the evaluation. WPCC selected a hollow build style called 10% triangular infill and used a 0.2mm skin thickness. They used the system to build patterns for prototype patterns and have now been using the system for nearly a year.

Printer Performance

Build Envelope – Build envelope determines not only how large a part can be built in one piece but also how many smaller parts can be built at one time. The build envelope of the s5 is 13 x 9.5 x 11.8 inches. For simplicity, the three dimensions are multiplied together to obtain the volume of the build envelope. Figure 1 shows how the envelope of the test system compares to the four leading pattern printing systems.

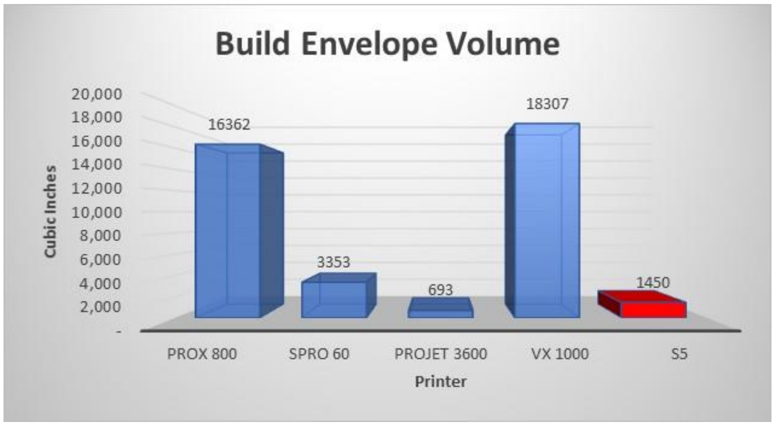


Figure 1. build envelope of the test system compared to leading pattern printers.

The build envelope of the s5 is small compared to the larger printers such as the Prox800 or the VX1000 but is larger than the envelope of the 3600. It is not large enough to accommodate all sizes of castings done by WPCC. However, they claim that it will build approximately 70% of the patterns they need in one piece.

Accuracy – Accuracy of AM systems is notoriously difficult to measure. It can vary with the orientation of the dimension relative to the build plane and can be affected by the layer thickness. WPCC claimed that the accuracy of the s5 was adequate for the castings they produce. Of course, accuracy requirements vary with the application for the casting. Other applications may require greater accuracy.

To get a better understanding of the accuracy of the test system relative to the more popular pattern printing systems, a test part was devised with 36 dimensions covering 3 coordinate directions and both inside and outside dimensions. The test part is shown in Figure 2.

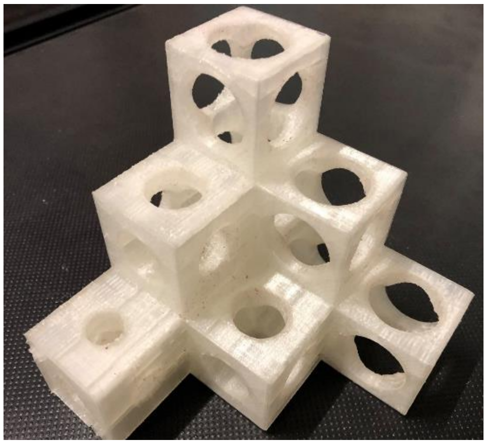


Figure 2. Accuracy test part.

WPCC built the test part using the s5. The University of Northern Iowa (UNI) also built the test part using QuickCast, printed wax and Voxeljet printers. UNI then measured each test part using their CMM system. The average absolute value of the dimensional error over the 36 dimensions is shown in Figure 3. Surprisingly, the s5 had the lowest average error. Given the extremely limited amount of data in the test, conclusions about the relative accuracy of the systems cannot be drawn. However, I think it is safe to say that the s5 accuracy is at least competitive in comparison to the more popular systems.

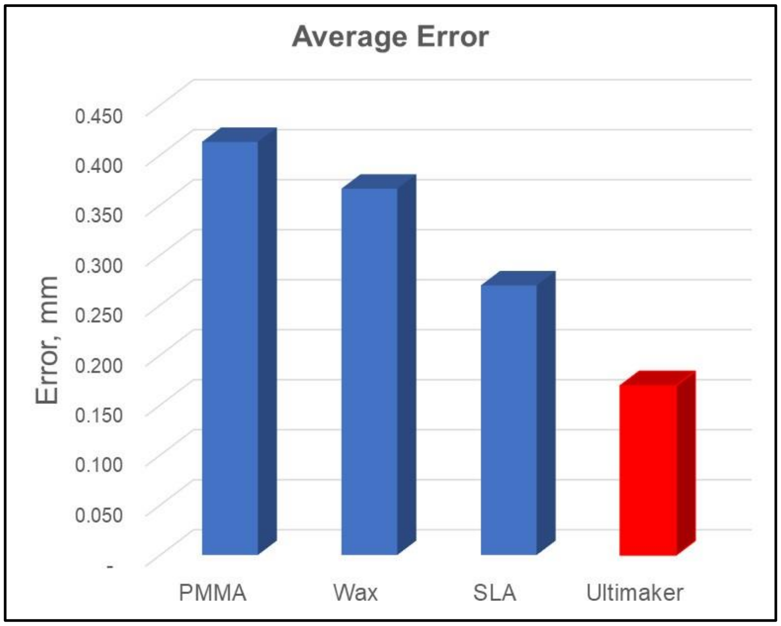


Figure 3. Average dimension error measured on the test part.

Surface Roughness – One of the advantages of the PolyCast filament is that it is vapor polishable. The process that WPCC used to finish the patterns after printing was to do some light sanding to knock down build lines and then about 20 minutes of vapor polishing using a small inexpensive unit. While we were not able to measure surface roughness, WPCC claimed it was well within requirements for the castings they produced.

Build Speed – Build speed can be difficult to define. Speed varies with the geometry of the part being built, the number of parts being built at the same time and other variables. The best approach is to determine an average build rate estimated from many builds. The approach I took in the study in 2016 was to gather data from service providers who used the systems in question to build printed patterns for investment foundries. I asked them to provide data from several runs. The data requested included 1) the total volume of patterns built on that run, and 2) the total build time for that run. The apparent build rate (ABR) for each run was calculated by dividing the total volume of patterns built by the total time to yield a rate in cubic inches per hour. The ABR is then averaged over the number of runs to estimate the average build rate for that system when building printed investment casting patterns. The number of data points for each system varied from a few dozen to several hundred.

WPCC provided the same data for several pattern builds. Build speed varied depending on the size of the nozzle used but the average for all runs was 2.14 cubic inches per hour. Figure 4 shows how the s5 average build rate compares to the more popular systems. The speed of the s5 is only 8% of the VX100, the fastest system, but is nearly twice that of the Projet 3600.

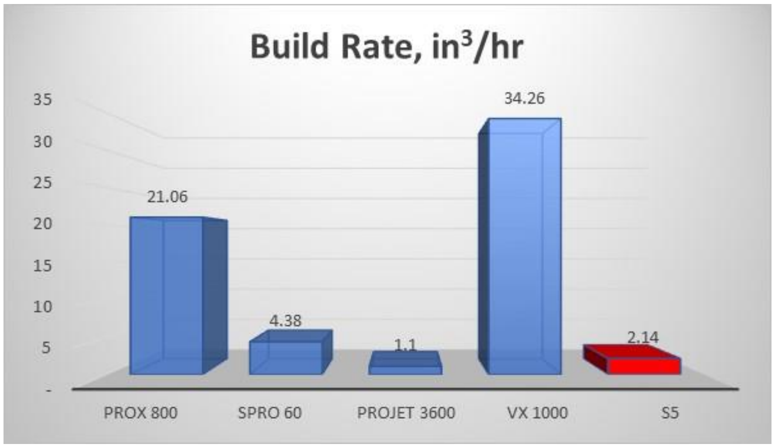


Figure 4. Average Built Rate of Pattern Printing Systems

Operating Cost

Printer Cost

The cost of the printer is an important consideration. Most foundries in North America are small businesses that have limited capital available. In addition, for most foundries castings made from printed patterns generate less than 10% of their revenues. It is hard to justify a major capital investment for a system that will only impact a small percentage of their revenues. An investment in a robot or software that will reduce cost on all their production may provide much better returns.

Figure 5, List prices for printers exclusive of assocaited equipment and facility modifications.

Figure 5 shows the purchase price for the s5 and the four printers from the previous study. Note that list prices are used for the comparison. Few people pay list price for the systems they purchase. However, finding actual average purchase price is exceedingly difficult so list prices are used. In addition, the prices only include the cost of the printer itself. Any needed associated equipment is not included, nor is any facility modification that may be required for the printing operation.

The s5 is significantly less expensive than the popular printers. Its cost is only 9% of the cost of the least expensive system and a little more than 1% of the cost of the most expensive system.

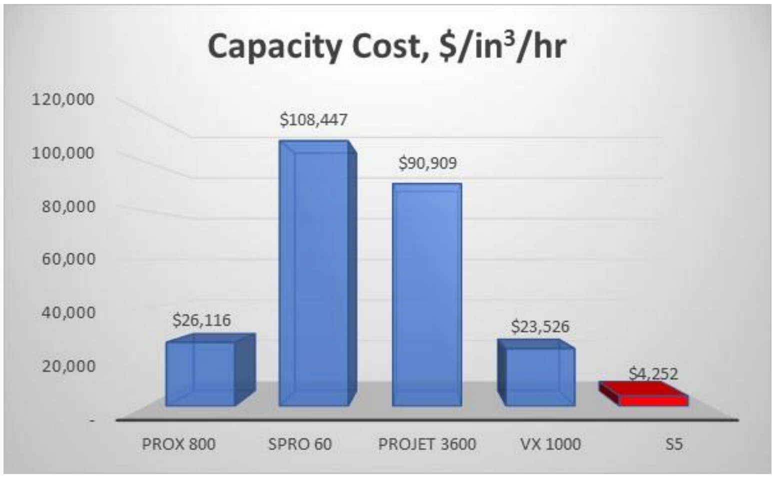


Figure 6. Capacity Cost for printers.

However, it is dangerous to only compare printer prices. The build speeds of these printers vary widely, and more expensive printers can print many times the volume of patterns per day than the less expensive systems. For a true apples-to-apples comparison, it is necessary to look at the "capacity cost". Capacity cost can be defined as the cost per one cubic inch per hour build rate and is determined by dividing the printer price by the build speed. Figure 6 shows the capacity cost for the s5 and the more popular systems. The s5 has the lowest capacity cost at less than 20% of that of the VX1000, the lowest of the more popular systems. Consequently, building a desired level of printing capacity will cost far less with low end industrial material extrusion printers than with any of the more popular systems.

Pattern Cost

The cost to print patterns is at least as important as the cost of the system itself.

The cost to print the pattern has four components: materials, depreciation, maintenance, and labor. Of these, labor is the most difficult to quantify and a case can be made that the labor required for file preparation, printing and post-processing is roughly equivalent regardless of the system used. Consequently, it is not considered in this analysis.

Figure 7. Material cost per cubic inch of pattern.

Materials – the cost of all materials consumed in the process, including the material process, the cost of supports, and any other materials involved in printing the patterns. In this analysis, the list prices of materials were used. For those processes that use supports, the volume of supports required in a print is very dependent on the design of the part being printed. For this analysis, it was assumed that the volume of supports was, on average, 50% of the volume of patterns. Figure 7 shows the cost per cubic inch of materials for the pattern printing processes.

Depreciation – a major cost of printing is depreciation on the printer used. For simplicity, a seven-year straight-line depreciation was assumed. For that case, the monthly depreciation cost is simply the purchase price of the system divided by 84 months. To get the cost in terms of dollars per cubic inch, however, we need to divide by the number of cubic inches of pattern built per month. To estimate the average number of cubic inches of pattern built per month, I assumed that the printer would, on average, be actively printing 16 hours per day for five days of the week, or a total of 80 hours per week. Some might think that printers would be used more than half of the available time, but in reality without staffing 24 hours per day and over weekends to start new jobs as soon as the previous one completes, it is difficult to consistently achieve more production than that.

The average monthly production can then be estimated by multiplying the average monthly printing hours by the average build rate. Figure 8 shows the estimate of the average monthly production of patterns for each of the five printers.

To estimate the depreciation cost per cubic inch, the monthly

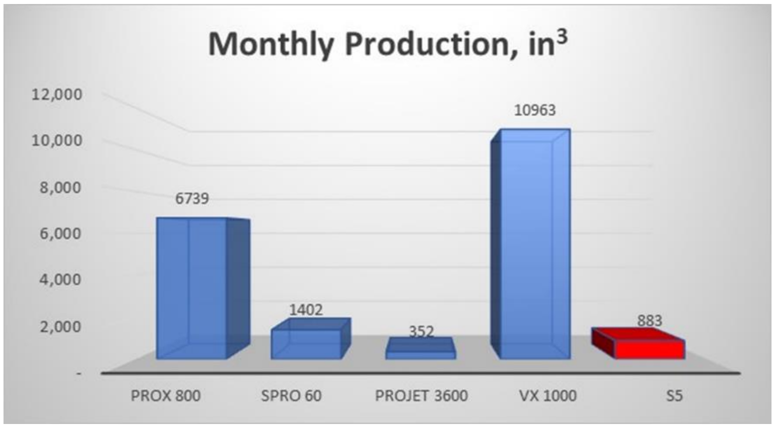


Figure 10. Average monthly pattern production

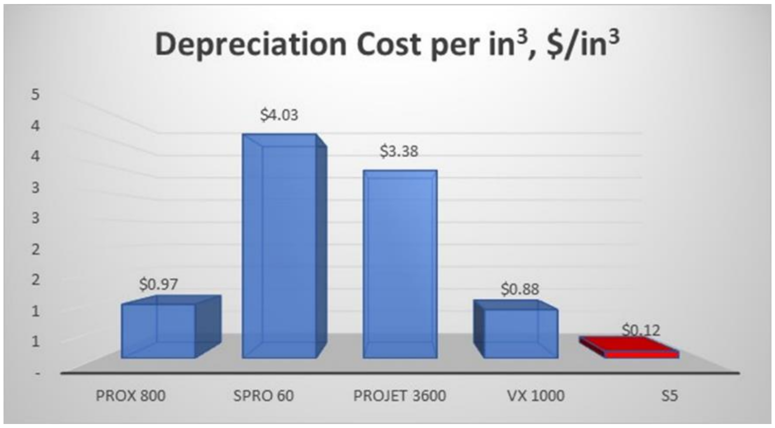


Figure 9. Depreciation cost per cubic inch of pattern.

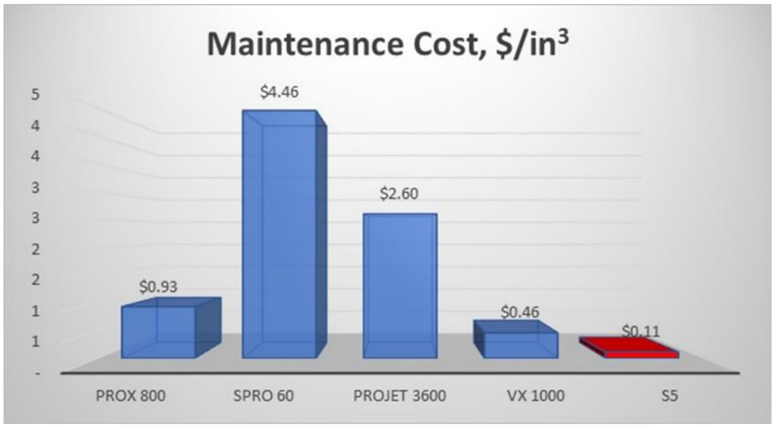


Figure 8. Maintenance Cost per cubic inch of pattern.

depreciation cost is divided by the average monthly production. Figure 9 shows the result for the five printers. The depreciation cost of the s5 is much lower than the other printers.

Maintenance Cost – Maintenance is a significant cost for AM systems, but it can be exceedingly difficult to get accurate information on maintenance costs. Users often do not maintain accurate records and if they do, they are reluctant to share the information. To estimate maintenance costs, I used the cost of the most comprehensive maintenance plan offered by each printer manufacturer. The most expensive plan typically covers even the most expensive components such as the laser on a stereolithography system or the printhead on a binder jetting system.

To estimate the maintenance cost per cubic inch, the monthly cost of the maintenance contract is divided by the average monthly production. Figure 10 shows the maintenance costs for the five printers.

Figure 11. total non-labor cost per cubic inch of pattern.

Total cost – Adding the three cost components yields the total non-labor costs for each of the systems. Figure 11 shows the results.

The s5 has the lowest total cost, approximately 1/3 of the cost of the least expensive of the more popular systems and less than 6% of the most expensive system.

The 2016 study included a chart that compared the popular systems based on two of the most important measures of performance for a foundry; build rate and pattern cost. Figure 12 displays that chart including the s5. The chart shows build speed on the x axis and build cost on the y axis. Each of the 5 printers is plotted on that chart. Systems with a high build speed and low cost will be the most attractive to a foundry. Those systems would be in the lower right portion of the chart. Those in the upper left portion of the chart would have a higher build cost and lower build speed.

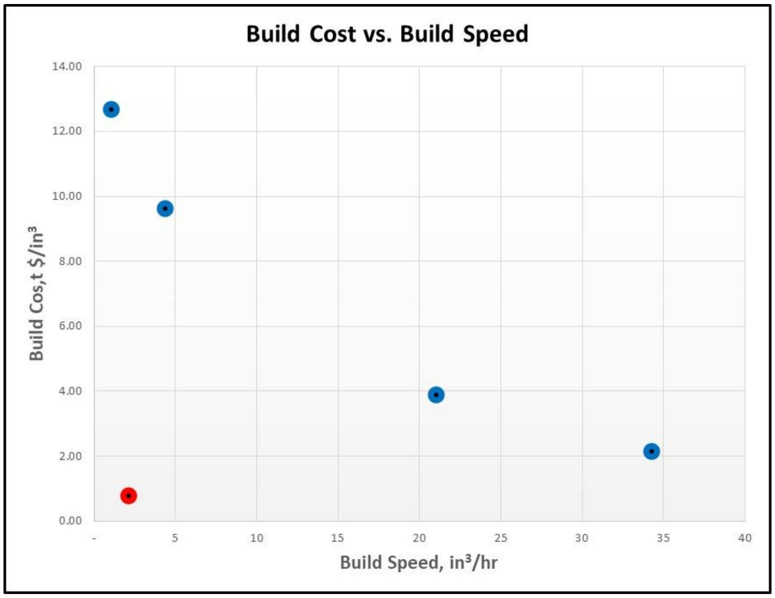


Figure 12. Build cost vs. build speed for the 5 systems.

This compares only two measures of system performance. A foundry might choose one of the less attractive systems in this chart for other reasons such as ease of casting.

The s5 is in the lower left portion of the chart with the lowest build cost but a low build speed. It is not in the more desirable lower right part of the chart but the use of multiple systems can effectively move the position. For example, consider a purchase ten s5 systems. The build cost per cubic inch of pattern would be the same but the effective build speed would be ten times higher, putting it at 214 cubic inches per hour, slightly higher than for a ProX 800. However, both the purchase price and pattern cost would be less than one-fifth that of the QuickCast system. In addition, if the QuickCast system goes down, printed pattern production stops until the printer is repaired. If one of the material extrusion printers goes down, 90% of the pattern printing capacity is still available. On the other hand, the QuickCast system could build larger patterns than the s5.

Ease of Casting

One of the biggest considerations for a foundry in choosing a pattern printing technology, whether using in-house printing capacity or buying patterns from a service provider, is how difficult it is to convert the printed pattern to a saleable casting. For most of the pattern technologies, variations to the process used for molded wax patterns are required to yield an acceptable casting.

Obviously, using printed patterns eliminates the need for creating tooling and molding patterns. Casting printed patterns generally requires modifications to two of the major steps in the investment casting process. Those steps are:

1. **Assembly** – Typically, printed patterns are attached to a common molded wax sprue and attaching the patterns is straightforward. However, because most patterns must be burned out of the shell rather than melted, it is important that oxygen is available in the shell to support the combustion. In many cases, it is necessary to add vents to each mold in the assembly to provide a path for airflow through the shell. For QuickCast patterns, the vents also allow steam to enter the pattern in the autoclave, softening the pattern material so that the pattern can collapse as it expands instead of cracking the shell.

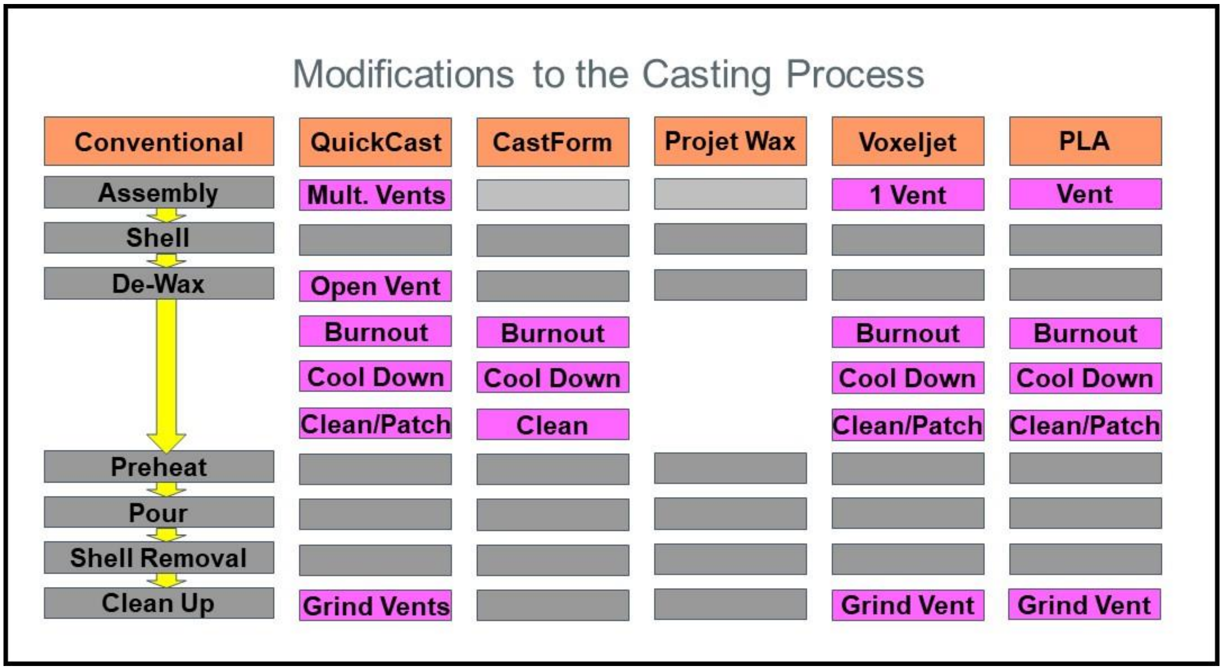
2. **De-Wax** – The de-wax step is to remove the patterns from the shell. For printed wax, the same process used for molded wax patterns can be used. For the other pattern printing methods, however, the pattern will not melt out of the shell at normal autoclave temperatures and must therefore be burned out of the shell. For those foundries using a flashfire de-wax system, pattern burnout can typically be achieved with the flashfire system. For foundries using an autoclave, however, burnout is usually a three-step process.

a. ***Autoclave*** - First, the shell is autoclaved to remove any wax components of the assembly, including the sprue and runners. If vents have been added to the assembly, the vents must typically be opened prior to the autoclave step.

b. ***Burnout*** – The autoclaved shell is then placed in an oven to burn out the patterns. It may be necessary to lower the oven temperature to avoid cristobalite formation for fused silica shells. It may also be necessary to add oxygen to the furnace atmosphere and encourage airflow through the shell to replenish oxygen consumed in the combustion process.

c. ***Cleanout*** – After burnout, the shell typically is cooled to room temperature and any ash remaining in the shell is blown out or rinsed out. Any vents are patched at this point as well.

Figure 13 details the modifications to the casting process necessary for each of the five pattern printing technologies.



Modifications to the Casting Process

Conventional	QuickCast	CastForm	Projet Wax	Voxeljet	PLA
Assembly	Mult. Vents			1 Vent	Vent
Shell					
De-Wax	Open Vent				
	Burnout	Burnout		Burnout	Burnout
	Cool Down	Cool Down		Cool Down	Cool Down
	Clean/Patch	Clean		Clean/Patch	Clean/Patch
Preheat					
Pour					
Shell Removal					
Clean Up	Grind Vents			Grind Vent	Grind Vent

Figure 13. Comparison of investment casting process variations necessary for each of the pattern printing technologies.

The inkjet Projet wax patterns are the easiest to cast. They require no modifications to the conventional casting process.

Castform patterns are a little more difficult. The patterns must be burned out of the shell, but they are reportedly pretty easily burned with little residual ash. No venting is typically necessary.

The three remaining processes all require some venting to provide airflow through the mold during burnout. In addition, they typically require a cool down of the shell after burnout to clean out any residual ash and patch vents prior to preheat and pouring. The amount of venting varies with the process.

QuickCast patterns typically require the most venting. In QuickCast patterns, venting also serves to allow steam to enter the pattern in the autoclave. The steam softens the internal support structure and allows the pattern to collapse inwardly as the pattern expands with heat. It is important that steam penetrates the pattern immediately upon pressurization. As a result, larger patterns may require multiple vents per mold. Without the venting, cracking of the shell due to thermal expansion of the pattern is possible if not likely. Shell cracking is the most common cause of failure for QuickCast patterns. The vents will at a minimum leave witness marks, if not a stub, which must be removed in the process of finishing the casting.

Voxeljet PMMA patterns have an extremely low expansion rate but are solid, unlike the QuickCast or PLA patterns. As a result, more oxygen is required for combustion and more ash will be generated, even if the residual ash percentage is similar to those for resins for QuickCast. Because it is not necessary to allow steam into the interior of the pattern, fewer vents are necessary.

In WPCC’s experience, the difficulty in casting PLA patterns lies between that for Voxeljet and QuickCast patterns. Initially, they tried using the same process as for molded wax patterns and had quite a bit of success for small castings. They did not see significant ash related defects or other issues.

For larger castings, however, they found some shell cracking issues and reverted to the process they use for QuickCast patterns. As in casting Voxeljet patterns, they used only one vent per mold. They have had good success with that process.

The five processes can be ranked in order of increasing ease of casting:

1. Projet printed wax
2. Castform
3. Voxeljet PMMA
4. PLA
5. QuickCast

Summary

Table 1 summarizes the findings for the s5 printer running the PolyCast filament.

Evaluation Criteria	Results
Build Envelope	Acceptable for many foundries
Accuracy	Competitive
Surface Roughness	Acceptable for many investment casting applications
Build Speed	Faster than printed wax
System Cost	Lowest printer price and capacity cost
Pattern Cost	Lowest pattern cost
Casting Difficulty	Slightly easier than QuickCast

Table 1. Summary of results

Conclusions

1. The Ultimaker s5 printer running the PolyCast material provides acceptable performance in printing investment casting patterns relative to more popular systems.

2. Low-cost industrial material extrusion printers running filaments specifically developed for investment casting are viable for printing investment casting patterns.

3. Such low-cost systems provide a low risk means for foundries to bring pattern printing capability in-house because:
    a. Printer cost is extremely low compared to more popular systems
    b. Capacity cost is much lower than the more popular systems
    c. Necessary associated equipment cost is low
    d. Facility modifications are typically not required
    e. Pattern cost is lower than more popular systems
    f. The printer provides acceptable performance
    g. Patterns are no more difficult to cast than QuickCast patterns