# An Overview of Additive Manufacturing Applications in Investment Casting

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## Background

It is nearly 30 years since the first applications of additive manufacturing (AM), then called rapid prototyping, were introduced in the investment casting industry. While they have not received the attention that other AM applications have, probably because they create an intermediate step in the casting process rather than the end product, AM applications in investment casting have been among the most successful given how universally they have been adopted in industry.

This document, produced for the Investment Casting Institute, is designed to educate the ICI membership about AM and how it can be used profitably in the investment casting process and to improve their ability to compete.

## Applications of AM in Investment Casting

Over these nearly three decades since AM was first used in investment casting, multiple areas of application have developed. They include:

1. Printed Patterns
2. Printed Ceramics
3. Tooling Applications

Each of these areas is addressed on following pages.

### Printed Patterns

Printed patterns were the first application of AM in IC and are by far, the largest. The advantage of being able to create castings without first building a tool is obvious and drove development of the application early in the development of additive manufacturing. Over time, the use of printed patterns has been adopted for several purposes.

#### *How are printed patterns being used?*

There are five primary ways that printed patterns are being used today.

- **Prototype Castings** – Prior to the development of printed patterns, the only way to create prototype investment casting was create a tool in which wax patterns could be molded. As a result, there was a large investment in both cost and time to obtain a prototype casting. If testing of the prototype determined that design changes are required, additional investment in both cost and time are required for tooling modifications. Pressure to get the product to market often means that the first acceptable design is adopted even if it is not the best design.

The use of printed patterns to create prototype castings dramatically changes that situation. Even though the printed pattern is significantly more expensive than the cost of molding a wax pattern, eliminating the cost of tooling greatly reduces the cost of the prototype casting. In addition, the lead time is much shorter. Consequently, upfront investment in cost and time to get a prototype casting is drastically reduced. Using printed patterns, designers could go through additional design iterations resulting in better designs that were previously possible. In addition, to reduce time further, they can evaluate multiple design alternatives simultaneously, something that was prohibitively expensive with molded wax patterns.

Using printed patterns for prototype castings also provides benefits to the foundry. It allows them to get experience with the casting and identify issues that could affect the profitability of a production run before they have to provide a quote for production castings to the customer.

The use of printed patterns to create prototype castings has achieved nearly universal adoption. Nearly every foundry in North American uses printed patterns to supply prototype castings to their customers. It has been one of the most successful applications of AM even though it is not often recognized, probably because it creates an intermediate step in the casting process rather than the final component.

- **Bridge Production** – This term is used to describe using printed patterns to create production castings until wax pattern tooling is completed. The casting is most often one component out of several in a product being developed. Once the casting design has been finalized (after testing of the prototype casting), the order for tooling is released and it will be weeks or months until the tool is delivered, and wax patterns can be molded. However, some aspects of product development are delayed until production castings are available. For example, field trial units cannot be built and distributed. The resulting delay in market introduction can affect the profitability of the product. To avoid that, many companies use printed patterns to make a limited number of production castings so that they can continue product development efforts while waiting for wax pattern tooling to be completed. This application has grown tremendously over the last several years.

- **Very Low Volume Production** – Before AM, the cost of tooling prevented investment casting from being a cost-effective manufacturing process for projects where the number of components required was low. For example, if a particular job required 20 castings, the amortized cost of tooling usually pushed the part price well above competing manufacturing processes such as machining. The ability to print patterns changes the economics of the situation tremendously. Eliminating the cost of tooling makes investment casting much more competitive. This has opened a new market for the investment casting industry. In many cases, the cost of machining the component is much higher than the cost of casting with printed patterns and allows the foundry to charge prices that earn higher margins than is possible on higher volume orders and still be less expensive than machining. Some foundries have found this to be a lucrative source of business.

- **Process Development** – Some aspects of the investment casting process cannot be finalized until the first castings are produced. Examples include verifying actual shrink values, verifying dip robot manipulations to ensure even slurry coverage, and determining the need for and design of straightening fixtures. All these activities can delay the start of production once tooling is available. All these tasks, however, can be accomplished using castings made from printed patterns while tooling is being created, minimizing any potential delays of production. This application of printed patterns has not yet been widely adopted but can be extremely valuable, especially for unusual casting designs.

- **Complex or Un-moldable Geometry** – Investment casting with molded wax patterns requires that the design be economically moldable. The development of topology optimization and generative design technologies have been able to create designs that significantly reduce the weight of components without sacrificing strength. Unfortunately, most of the designs are not easily moldable and consequently cannot be manufactured with conventional investment casting. It is generally assumed that such designs will ultimately be created using metal printing. Most of these designs, however, be cast using printed patterns. While this is currently the least used application of printed patterns, it is anticipated that it will quickly gain popularity once designers become aware that complex castings can be cost effectively manufactured using printed patterns and will be significantly less expensive than metal printing, especially for larger parts. Printed patterns also provide a higher potential to enable a cast component to replace assemblies of components. Such complex components will be another new market for the industry.

### *What kinds of AM technologies are used to print patterns?*

There are now several AM technologies that can print patterns for investment casting. Following are the most popular AM technologies used for printing investment casting patterns.

- **Stereolithography** – Stereolithography (SL) is the oldest AM technology and the first one used to print patterns. Solid patterns are problematic because thermal expansion of the pattern will crack the shell in the autoclave or in the furnace. Consequently, many manufacturers have developed build styles to create hollow patterns. The most common SLA pattern printing process is the QuickCast® process but there are competing processes.

- **Laser Sintering** – Laser Sintering (LS) printers typically use a polystyrene powder to create investment casting patterns which is fused together using a laser. The finished pattern is typically dipped in liquid wax to seal the surface. and increase strength. The most common LS pattern printing process is marketed under the tradename Castform®, but there are competing processes from other manufacturers.

- **Material Jetting** – Material jetting (MJ) systems use inkjet printing technology to jet tiny droplets of material to build parts. For investment casting applications, they jet wax. MJ systems have the advantage of creating wax patterns which are easier to convert to castings than those provided by other technologies. At least two manufacturers provide printers using the MJ technology.

- **Binder Jetting** – Binder jetting (BJ) systems use inkjet printing technology to jet droplets of a binder onto a power bed to create solid material. Various powdered materials have been used for investment casting applications including starch and plaster. The most common material in use today is polymethylmethacrylate (PMMA) used in Voxeljet systems.

- **Digital Light Processing** – DLP technology, like stereolithography, uses a photocurable resin. However, instead of using a laser to solidify the resin, DLP systems use a digital projector chip, like those use in projection televisions to cure an entire layer at once. Multiple manufacturers provide DLP printers used to create printed patterns.

- **Material Extrusion** – Material extrusion (ME) printers extrude out thermoplastic materials in thin layers. Most commonly material is supplied to the printhead in a filament, but some printers are now using pelletized material which is melted prior to delivery to the printhead. Several manufacturers sell ME printers that can be used to print patterns and they are gaining in popularity.

### *Why aren't printed patterns used for higher volume production?*

Many observers predicted that printed patterns would displace molded wax as the primary means of creating investment casting patterns. That certainly has not been the case. While printed patterns have been overwhelmingly adopted for prototype castings and are increasingly used for low volume production, they are rarely if ever used for even medium volume production. There are several reasons that printed patterns are not used for volume production.

- **They are too expensive** – While printed patterns are significantly less expensive than wax pattern tooling, they are much more expensive than the cost of a molded wax pattern without amortized tooling cost. Consequently, after several castings, the total cost of printed patterns will exceed the cost of tooling plus molding that number of wax patterns. That number of castings is called the cost-breakeven quantity. At quantities higher than the cost-breakeven quantity, it is more expensive to use printed patterns than molded wax patterns. The cost-breakeven quantity varies with the size and complexity of the casting design, but for most castings, it is in the range of 10-50 castings. It simply is not cost effective to use printed patterns for orders greater than the cost-breakeven quantity.

- **They are too slow** – Cycle times for molded wax patterns are typically a few minutes or less. Build times for printed patterns, on the other hand, is typically measure in hours and for larger patterns, days. Matching the production rate of a single wax injection press would require several printers at a cost likely orders of magnitude greater than the cost of the press.

- **They don't have the necessary quality** – The surface roughness of printed patterns right out of the printer is often not adequate to meet the surface roughness requirements of the casting. To meet those requirements, post-processing is required and that usually means manual labor, further increasing the cost of the pattern.

- **They are too difficult to cast** – With the exception of MJ wax patterns, each of the above processes require that the pattern be burned out of the shell rather than melted. As a result, there are modifications to the process used to cast molded wax patterns. While the modifications apply to only two steps in the process, failure to use the modified procedure will almost certainly result in a failed casting and the loss of the cost of the pattern as well as the cost of the casting process including assembly, shelling, autoclaving, preheat and casting. Most foundries just pour a few prototype castings each week and keeping track of those few assemblies is relatively easy to do. However, if a foundry used printed patterns for twenty or thirty percent of their production, trying to keep track of which shell require which process step would become a nightmare.

These are the reasons that printed patterns are not used for volume production today. However, advancements in the industry are gradually eliminating those issues and the situation may change completely over the next several years.

### *What are trends in printed patterns?*

Changes are coming quickly to printed patterns. Some of the primary ones include:

1. **Printers are getting faster** – Some of the newer printers, particularly DLP systems, are much faster than earlier systems. Some claim to be as much as 50 times as fast as the older SLA systems.

2. **Materials are getting cheaper** – Some of the newer technologies, particularly ME printers use much less expensive materials. Higher volumes and competitive pressures are reducing material costs on even the older systems.

3. **Printers are getting cheaper –** Many of the newer technology printers, particularly ME and DLP are significantly less expensive that many of the older technologies. Some ME printers cost less than $10,000 and are in use in foundries today. Even the prices of the older technologies have come down considerably although they are still much more expensive.

4. **Build Envelopes are getting bigger** – Several material extrusion printers are now available with build envelopes in the range of one meter cubed. A binder jet printer with a build envelope of two meters by a meter by a meter has been announced.

5. **Post-processing is becoming automated** - Post processing (finishing of the patterns after printing to improve surface finish) has traditionally been a manual labor process that added time and cost to the pattern. Now there are several companies that sell automated finishing systems that eliminate much of the labor and reduce costs.

6. **The cost of printed patterns is coming down quickly** – many of the above items are contributing to the lower cost of patterns. Less expensive printers and faster build speeds reduce the depreciation component of pattern cost. Less expensive materials reduce the material component. Automated post processing reduces the labor components. As a result, the cost penalty of printed patterns compared to molded patterns is getting smaller. This means the cost-breakeven quantity is getting higher.

7. **The casting process is becoming less complicated** – new developments in venting and the burnout process are minimizing the variations in the casting process between printed patterns and molded wax patterns.

8. **Foundries are bringing capability in-house** – the lower cost of both printers and materials are making it easier for even small foundries to purchase pattern printing capability. They are justifying the expense through reduced purchases of printed patterns and faster availability of patterns.

9. **Printer automation is coming** – All AM printers available today are batch printers. In other words, an operator must start the build and when complete, an operator must unload the machine before the next build can begin. No commercially available pattern printer yet has the capability to automatically unload the printer at the end of the build and start the next job. Consequently, when a build completes late at night when no one is around, the printer sits idle until someone unloads it and starts the next job the next day. Adding the job changing capability described above will significantly increase the productivity of pattern printers.

# Printed Ceramics

There has been quite a bit of interest in recent years in printing ceramics for the investment casting process. There are three potential applications for printed ceramics in investment casting.

1. Printed cores
2. Printed filters
3. Printed shells

Most of the effort has been concentrated in printing ceramic cores but there also have been developments in the other areas.

Like molded ceramics, the printing process creates a "green" part. The green part is fragile and must then be sintered at high temperatures to densify the ceramic increasing both its ability to withstand the heat of the casting process and the forces exerted on it.

## Printed Cores

Like molded wax patterns, ceramic cores require tooling, and the tooling requires an upfront investment and lead time, a delay between the time that the core design is finalized, and a tool is available to mold cores. The ability to print ceramic cores provides benefits like those provided by the ability to print patterns. It allows a casting that requires ceramic cores to be evaluated faster and at lower cost than is possible with conventional processes.

Of particular interest is the ability to print core geometries that cannot be molded. Analysis has suggested that improved cooling can be achieved in turbine blades by using a multi-wall or "folded" cooling channel within the blade. The improved cooling increases the operating temperature of the turbine which increases the efficiency of the turbine. Even small increases in efficiency can greatly increase the profitability of the turbine. Ceramic cores to create such a cooling channel cannot be molded but potentially can be printed.

Printing ceramic cores is significantly more challenging than printing patterns. First the material must withstand the heat of molten metal but be able to be removed from the casting after solidification.

Secondly, the core as printed is notoriously fragile and must be sintered to improve the strength and the ability to withstand the heat of molten metal.

## Core Printing Technologies

To date, there are two primary technologies used to print cores.

1. **Digital Light Processing** – DLP is the printing process used by most of the suppliers of printed ceramics for investment casting. The DLP process uses a photocurable resin heavily filled with ceramic powder.
2. **Binder Jet** – BJ systems use a ceramic powder as the base material. A binding agent is jetted onto the powder to selectively solidify the material as needed.

### *Using Printed Cores*

It is possible to use printed cores with wax pattern tooling, the same way that molded ceramic cores are used. This can be an effective way to optimize core design, especially for flow passages. More often, however, printed cores are used to create prototype castings for designs that will require ceramic cores. For those situations, it is necessary to create a cored pattern, an assembly of a printed core inside a printed pattern. The printed pattern must be split and hollowed so that it can be assembled around the core. The assembly is glued together and sealed to ensure that slurry cannot seep into the interior of the pattern. At least two companies provide core printing services.

Like molded ceramic cores, printed cores will require core prints that will become embedded in the shell as it builds and holds the core in place.

## Printed Filters

A few companies have developed the ability to print ceramic filters. They have demonstrated that printed filters provide advantages over the commonly used ceramic foam filters. Printed filters can more tightly control the pore size distribution of the filter and significantly reduce the probability that particles will pass through it. Providers claim that ceramic foam filters may have loose ceramic particles in the filter that can he carried into the mold with the molten metal. The particle is then an inclusion that is a potential crack propagation site. In addition, the engineered structure greatly reduces filter-to-filter flow rate variability as compared to the organic reticulated ceramic foam filters and can serve double duty as flow-control devices.

Printed filters are primarily created using extrusion deposition, printed foam replication or DLP processes.

Printed filters are significantly more expensive than typical foam filters used in low-value castings. They are often cost competitive with foam filters used on high value, highly stressed castings where even a tiny inclusion could have catastrophic results.

## Printed Shells

In the past few years, there has been some work to develop the capability to print ceramic shells. To date, all efforts to print shells have used a DLP process.

Printed shells offer several potential advantages over conventional investment casting and hybrid investment casting where printed patterns are used.

1. **Complex Geometries** – Printed shells can create geometry that would be difficult or impossible to create with conventional shelling methods. For example, tight spacing on cooling fins would likely be impossible to shell but would be straightforward with printed shells.

2. **Integral Cores** – Cores can be printed in place inside the shell. Since they are printed with the shell, there is no opportunity for the core to be out of position relative to the cavity as it can be if the core is not positioned properly in the wax pattern die when over-molded.

3. **Ability to vary shell thickness to control heat transfer** – Normally, there is no ability to vary the shell thickness in different areas of a conventionally built shell. With a printed shell, however, the thickness of the shell can be varied to increase or decrease conductive heat transfer through the shell in that area. Cooling fins could even be added in some areas to increase cooling in a local area. It could also be possible to create pockets into which chills could be inserted prior to pouring to speed solidification in certain areas. Such capability could increase the ability to control material properties in different areas of the casting.

4. **Less disruption for the foundry** – If a foundry purchases a printed shell to create a prototype casting, they need only preheat the shell and pour. If they instead purchase printed patterns, they must interrupt normal production to create the assembly, build the shell, autoclave the shell, burnout the pattern, cleanout any ash in the shell and patch vents, before they get to the pre-heat step. It is a much cleaner process for the foundry , is easier to mix in with their normal production flow, and reduces their risk in prototyping.

5. **Integral filters** – Along with shell and cores, filters could be printed in place and in areas that would not normally be accessible.

6. **Sprues and gating optimized for laminar flow** – It would be prohibitively expensive to mold custom sprues for every casting application to avoid turbulence and air entrapment, but it can easily be done with printed shells. Custom sprues could result in improved castings.

7. **Material handling features** – A printed shell could incorporate features to enable robotic handling of shells. Such features could make it easier to use robots instead of manual labor to handle shells in hazardous steps of the casting process such as transferring shells from a hot furnace to a pouring floor. It could also be possible to print a flat base or legs on a shell so it can be self-supporting instead of being pushed into a sand bed.

While there are multiple development efforts in process, the only use of printed shells has been in demonstration projects. Commercially available printers and shell printing services are expected in the next few years.

## Trends in Printed Ceramics

1. **Larger Build envelope** – Early printers to create printed cores had build envelopes with a maximum dimension of only a few inches. This was a significant limitation. Binder jet

printers tend to have larger build envelopes. DLP printers with larger build envelopes are in development.

2. **Faster Build speeds** – both DLP and BJ systems can potentially be much faster than current systems as has been demonstrated on printers using those processes but developed for other applications.

3. **Improved Materials** – There is significant ongoing research to develop ceramics for the printing process that will have higher green strength, higher strength after sintering and better leachability.

## Printed Tooling

Investment foundries use several types of tooling in addition to wax pattern molds. Examples include setters, assembly fixture, inspection fixtures, straightening fixtures and machining fixtures. These types of tooling are not used for every casting but are used when needed. In some cases, metal fixtures will be required to support the weight of the casting or the forces involved in the operation. Others, however, do not involve high forces and in those cases metal tooling may not be required.

There are few published cases of AM being used for any investment tooling applications. There is potential, however, that some of these tooling applications can be printed on an AM system. If the foundry owns one, it is likely that they will be able to create the tool faster and less expensively than fabricating it.

1. **Setters** – Setters, or pattern cooling fixtures are used to hold patterns in position while they finish cooling. Patterns are ejected from the mold while they are still warm and somewhat flexible. In that state, some geometries can deform under their own weight and become fixed in the deformed position. Setters are used to hold the patterns in position until they are cool and no longer will deform. Since the loading is only the weight of the pattern, AM can be used to create setters quickly. Foundry engineers can easily create setting fixtures from the casting design using CAD tools and by printing them inhouse, they typically save both time and money.

2. **Inspection Fixture** – Occasionally it is necessary to measure dimensions that are difficult to measure without a CMM. In some cases, the use of an inspection fixture can simplify those measurement so that simpler tools such as calipers or height gages can be used. The fixture typically must support the weight of the pattern or the casting. For most patterns and small castings, fixtures printed in a plastic material such as ABS will likely perform well. Heavier castings could use metal printed fixtures. In either case, it may offer foundries the capability to save time and money by printing their own fixtures.

3. **Machining Fixtures** – Machining fixtures not only need to support the weight of the casting, but also any forces exerted on the casting from the machining process. These forces rule out plastic AM fixture for larger castings and many small castings. However, AM with plastic materials may be used for some small castings. Metal AM fixtures likely can be used for the remainder.

4. **Straightening Fixtures** – Given the forces involved in straightening, it is doubtful that a plastic AM fixture could be used. Metal AM fixtures might be used but even that is questionable.

5. **Wax Pattern Molds** – There has been interest in printing wax pattern molds, especially for low volume or prototype applications. There are few if any documented success stories. However, new AM materials have much higher heat deflection temperatures and strength than older materials. It should be possible to print viable wax pattern tools that will withstand the temperature and pressure in a wax molding environment. The challenge will be to transfer heat out of the tool fast enough to provide reasonable cycle times.

## Summary

In the nearly 30 years that additive manufacturing has been used in investment casting, it has been adopted almost universally for prototype casting applications. However, there are many more potential applications yet to be evaluated and developed. There is no question that AM will play an increasing role in the industry and will help to improve both the range of applications for which investment casting is a competitive manufacturing process and the ability of investment casting to compete on both delivery time and cost compared to other metal manufacturing processes.