Cast metal parts

by Tom Mueller and Terry Wohlers

Additive manufacturing (AM) processes have long had applications in metal casting. Since the first systems emerged, attempts have been made to use their capabilities to reduce the time and cost of metal castings. The success of AM techniques in metal-casting applications varies considerably from one casting process to the next.

Investment casting

Among all the methods of metal casting, AM has had the greatest impact on investment casting. AM can aid investment casting mainly in four ways: printed patterns, printed ceramic cores, printed ceramic shells, and printed wax molds.

Printed patterns. Virtually any AM process can make patterns that can be used for investment casting. Some work much better than others. The majority of patterns are created by one of following methods of AM:

QuickCast: QuickCast is a trade name for a stereolithography build style from 3D Systems. The pattern is built mostly hollow with internal support structures. The build style minimizes the amount of material that must be burned out of the shell. It also prevents shell cracking in the de-wax step of the casting process. Shell cracking from thermal expansion during de-wax is the most common form of failure in 3D-printed casting patterns. The mostly hollow pattern allows it to collapse inwardly instead of swelling and cracking the shell. It remains a popular option, especially in North America, and it is the most common form of 3D-printed pattern for metal castings. QuickCast patterns, in general, provide very good accuracy and surface finish.

Vat photopolymerization (VPP): In addition to QuickCast from 3D Systems, a growing number of manufacturers and material suppliers offer photopolymers for investment-casting applications. Among them are Asiga, Carima, DSM Somos, DWS, Envisiontec, and Rapid Shape.

Material jetting (MJT): Solidscape was the first company using the MJT process to offer investment-casting patterns and remains a popular choice, especially for jewelry. 3D Systems first offered ThermoJet printers, followed by its ProJet CP and CPX systems. Most recently, the company offers the MJP 2500 IC system, specifically tailored for the investment-casting industry. MJT systems from Solidscape and 3D Systems create wax patterns that are very easy for foundries to use.

Powder bed fusion (PBF): PBF processes from both EOS and 3D Systems are used to create polystyrene parts that are then sealed with molten wax. PBF processes have lost ground in investment-casting applications to other AM technologies over the past several years, especially in North America.

Binder jetting (BJT): Voxeljet's BJT systems can produce investment-casting patterns in polymethylmethacrylate (PMMA). Voxeljet patterns are popular in Europe and are gaining ground in North America.

Material extrusion (MEX): ABS parts from Stratasys systems have been used for many years, but this process has never really gained a foothold in investment-casting applications. In recent years, the low-end industrial MEX systems have begun to be used to produce investment-casting patterns in polylactic acid (PLA). The accuracy and surface finish is inferior to more established methods. However, the low cost of printers and material have made it easy for foundries to reduce the cost of prototype patterns by bringing capabilities in-house. As the output quality of low-cost MEX systems improves, it is expected that their share of the patterns market will continue to increase.

Investment-casting patterns from AM processes are used in the following four main areas:

Prototype castings: Patterns from AM allow castings to be created without investing time and money in pattern tooling. Consequently, companies can quickly and inexpensively create near-production-quality prototypes to test a design. These patterns for prototyping allow designers to evaluate several competing designs simultaneously. Also, designers can produce more design iterations than are possible using conventional wax pattern tooling.

Process development: A number of steps in the development of the casting process require patterns. Consequently, they are typically not completed until after the delivery of wax pattern tooling. Such steps include optimizing gate locations, optimizing casting assemblies, determining local shrink values, robotic dip programming, and designing straightening fixtures. By using AM patterns, all these steps can be completed prior to delivery of the tooling, allowing faster delivery of the production castings.

Initial delivery of production castings: The quality of AM patterns, especially stereolithography patterns, has improved to the point where they rival molded wax patterns. In fact, they are accepted in many industries for production casting applications. Consequently, foundries can use these patterns to create initial deliveries of castings while wax pattern tooling is being produced.

Low-volume production castings: The ability to create production-quality patterns without wax pattern tooling enables investment casting to compete effectively with the machining of low-volume metal components. Previously, investment casting could not be justified for low volumes due to the cost of tooling. For more complex shapes, investment casting with AM patterns can provide significant savings in both time and money when compared to machining. A number of foundries are capitalizing on this new market. Low-volume production castings also provide better margins than conventional investment casting. Also, low-volume, short lead time production is less likely to experience significant foreign competition.

The use of AM patterns has gained widespread acceptance. Since 2000, the number of investment-casting foundries that have developed the ability to use AM patterns has increased rapidly. In North America, the increase has been from about 5% to more than 98%, but it is lower in Europe and Asia. An estimated 2% of investment castings in North America are created from AM patterns.

Currently, the majority of AM patterns are used for prototyping and very low-volume applications. In general, AM patterns have not been used for series production for three reasons. First, AM patterns are significantly more expensive than molded wax patterns at production volumes, even considering the cost of tooling. Any manual post-processing required to obtain a satisfactory surface finish adds to that cost and can even double it.

Second, AM processes are too slow to deliver large production volumes of patterns in the time frame needed. To match the production of wax-press molding patterns, several or even dozens of 3D printers would be required.

Finally, reliably casting most AM patterns requires variations to the normal process used to cast molded wax patterns. For example, most AM patterns must be burned out of the shell rather than melted out. The burnout process creates ash, which must be removed from the shell prior to pouring. These variations can be accommodated on an exception basis for prototype castings. However, they are very difficult to deal with if a significant portion of a foundry's production uses AM patterns.

While large-scale production of AM patterns is generally not yet feasible, it is anticipated that this situation will change over the next decade. Printers are becoming much faster and materials less expensive. Accuracy and surface finish are improving, thus reducing the need for manual post-processing. Also, improved casting technologies are minimizing the need for variations to the casting process for molded wax patterns. As a result, investment casting production will gradually move to printed patterns for those applications where it provides advantages.

A force driving that change will be the need to produce the complex geometries created by generative design and topology optimization software. These methods can reduce the weight of critical components while maintaining strength. This provides significant advantages in industries where weight is critical, such as aerospace, defense, motor sports, and automotive. Most of these designs, however, are very organic in appearance and the features are so complex that they cannot be molded. The common perception is that these designs will be created directly by metal 3D printing. However, studies have shown that investment casting can provide a lower cost and faster alternative to metal printing, especially as part size increases. Casting also produces a more well-studied metallurgy than sintering.

AM has especially taken hold in the jewelry industry. It is believed that thousands of AM systems are being used to make patterns for jewelry. In 2007, an estimated 2 million jewelry patterns were created on AM systems, such as those manufactured by Solidscape, Envisiontec, and 3D Systems. This resulted in the creation of more than $500 million in jewelry, excluding the value of the gemstones that were added.

Printed ceramic cores. Ceramic cores are used in investment casting to form undercut features that cannot be reliably shelled. Cores are typically created using a mold and an injection press. A few manufacturers have developed ceramic printers capable of printing ceramic cores. Lithoz from Austria uses a VPP process and a highly ceramic-loaded photopolymer to create cores. Admatec also uses a VPP process with a unique material delivery system using a tape. Other manufacturers are exploring BJT systems for making ceramic, but none have come to market.

Once perfected, a high demand could develop for the printing of ceramic cores that cannot be molded. For example, studies have shown that the gas turbine and jet engine efficiency can be increased by using complex internal cooling passages in the blades. Cooling passages are formed using a ceramic core, but the complex shapes required to achieve the higher efficiency cannot be molded. They can, however, be printed. The market is expected to grow quickly once ceramic printers are capable of creating cores with the required accuracy, strength, surface finish, and speed.

Printed ceramic shells. Some companies are developing ceramic printers that will print the ceramic shell rather than patterns. The advantage of printing the shell is that it eliminates a large part of the investment-casting foundry process. Printing the shell removes the need to mold patterns, assemble them onto a sprue, build a shell around the assembled patterns, and remove the patterns in the de-wax process. Those operations account for at least half the labor and floor space in a foundry and more than half of the capital investment.

Printing an acceptable ceramic shell, however, is complex. Some good results have been obtained for prototype castings, but no one has been able to meet the speed and cost required for production applications. Systems from Admatec, Lithoz, and Tethon3D are capable of directly printing ceramic molds and cores for investment casting in low volumes.

Printed wax molds. AM processes are also used to create tooling for molding wax patterns, although this application has not yet shown enough advantage to gain wide acceptance. This may change with the development of higher-temperature materials and the ability to build in conformal cooling channels. It is likely that printed wax molds will be used in the near future for low- to medium-volume production runs.

Sand, V-Process, and plaster mold casting

Sand, V-Process, and plaster mold casting are similar in that they all create cope-and-drag-type tooling and use inserts (called cores) to form undercut features. They differ primarily in the mold material used and the manner in which the mold is created. In each case, the mold is used once and then destroyed during the process of retrieving the casting.

Sand casting uses either compacted green sand or a chemically bonded sand to form the mold. It is the most widely used casting process and can be used for a wide variety of alloys and part sizes.

The V-Process uses unbonded sand for its molds. The mold is held in shape using a thin film of plastic and a vacuum. The plaster mold-casting process is very similar to sand casting except that plaster is used as the mold material instead of sand. All three processes use very similar tooling, called patterns, to create the mold. Different levels of complexity to the tooling are needed, depending on the number of molds that will be made. Most AM processes can be used to create patterns, but ABS patterns made on MEX printers have become particularly popular. They have the strength and abrasion resistance to stand up to the mold-making process and producing them is relatively quick and inexpensive. The adoption has been accelerated by the availability of low-cost industrial MEX systems, such as those from Cosine Additive and Stacker.

AM processes are also used to create core tooling. As was previously mentioned, cores are loose pieces placed in a mold to form undercut features and internal geometries. Cores are typically made of chemically bonded sand or plaster and are formed in molds called coreboxes. Cores are placed in molds very much like hand-loaded inserts are placed in a simple injection-molding tool. AM processes have been used to make simple coreboxes directly, and to make patterns against which epoxy coreboxes are cast.

Systems that create molds and cores directly

A number of manufacturers have developed AM processes that can build in plaster or sand materials. Using these systems, molds and cores can be built directly, eliminating the need for patterns and coreboxes. ExOne, Huake, Long Yuan, and Voxeljet offer systems that are capable of creating molds and cores.

Sand printing has gained acceptance as the fastest and least expensive way to create prototype sand castings. The cost of the machines is higher than most foundries can afford, but many service providers around the world produce and sell printed molds and cores.

Die casting

Die casting is the metal equivalent of injection molding. Die-casting tools have been produced using AM systems from POM, EOS, and others. Some of the tools have been successful, while others have not. Given the pressures and temperatures required in die casting, it is unlikely that AM processes will replace machined tooling in the foreseeable future.

AM processes are most often used to create prototypes of components that will ultimately be die cast. Patterns produced additively are often used with sand casting or plaster mold casting to create prototype castings. Although sand- and plaster mold castings often have significantly different properties than die-cast production components, they are sufficient for many prototyping applications.