Shape Casting: 5th International Symposium 2014
Edited by: Murat Tiryakioğlu, John Campbell, and Glenn Byczynski
TMS (The Minerals, Metals & Materials Society), 2014

Additive Manufacturing Supports the Production of Complex Castings

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Keywords: additive manufacturing, binder jetting, vat photopolymerization, fused filament fabrication, sand casting, investment casting

Abstract

Additive manufacturing is being used in a variety of ways to support the production of complex castings. Some of the common additive manufacturing processes include fused filament fabrication, vat photopolymerization, powder bed fusion, binder jetting, and material jetting. In this paper, the authors discuss the use of (i) binder jetting technology to fabricate sand molds for casting complex, cellular structures and (ii) fused filament fabrication & vat photopolymerization to produce complex investment casting patterns. Binder jetting of foundry sand molds allows the realization of cast structures that are impossible to mold using conventional methods. The structures are lightweight, multi-functional and may provide exceptional blast protection. With regards to investment casting, wax is currently the primary material used for producing expendable patterns due to a desirable combination of thermal expansion, thermal conductivity and melting point. However, wax is not a typical printed material. A variety of polymers are available for additive manufacturing and, as would be expected, only a few are suitable for use as expendable patterns for investment casting. The best polymers for use as expendable patterns for investment castings are PMMA, epoxy resin containing a reactive diluent and ABS.

Introduction

In today's fast paced, rapidly changing, economically sensitive market place, the ability to reduce product development time, and thus, rapidly introduce new products, at low cost is critical. Additive manufacturing is meeting this challenge. Additive manufacturing has been used in the casting industry for many years to quickly produce full-size models that engineers can examine and determine if their math models are correct and accurate. The casting industry quickly realized that these models could also be used as patterns to rapidly produce prototype castings, thus the phrase "rapid prototyping" was used in the foundry industry rather than "additive manufacturing". To produce a "rapid prototype", a computer-aided design (CAD) model is required, which was not the norm in pre-1990's manufacturing. But, times have changed, and most everything is designed (modeled) on computers today. With the change in the availability of CAD packages, the use of rapid prototyping has grown quickly and a wide variety of additive manufacturing techniques have been developed. The purpose of this paper is to describe how the shaped casting industry can use this "disruptive" technology.

Castings are used in 90% of all manufactured goods [1]. Castings can be produced from most any metal and may have simple or complex shapes. The molds that molten metals are poured into to produce a casting may be reusable, such as the metal molds used for gravity or high pressure die casting, or expendable, such as sand molds or ceramic investment casting molds. This paper focusses on expendable mold casting processes. Specifically, this paper describes how additive manufacture of sand molds and polymers can be used as “disruptive processes” to rapidly produce new, revolutionary casting concepts and complex shapes, which, here-to-fore were impossible or impractical to produce.

Molds for sand casting are typically produced by forming a combination of sand plus binder over a pattern. Since the sand mold must be removed from the pattern, the pattern must have draft and no undercuts; this greatly limits the shapes that can be produced. The molds also must have a parting line, i.e., the interface between the top and bottom molds. Dimensional tolerances are very good within a mold but the tolerance is much larger across a parting line since how well the two halves fit together is somewhat variable. To form internal passageways, bonded sand cores can be added. Sand molding is a versatile process and castings made using sand molding processes may weigh a few ounces to tens of tons.

Investment casting or the “lost wax” process has been used for the production of castings for centuries. In this casting process, an expendable pattern is coated with a ceramic, the expendable pattern is melted or burned out, the ceramic fired to attain sufficient strength, molten metal is poured into the ceramic mold and, after cooling, the ceramic is removed from the casting. Advantages of this process are high dimensional accuracy, excellent surface finish, ability to fill very thin sections (<1 mm is easily obtainable) and nearly unlimited shape capability. For high volume production, wax is typically injected into a metal die, which somewhat limits the shape capability. However, for the artist, any shape that can be formed from wax can be cast. An alternative to wax is polymers.

The characteristics of a desirable material for expendable patterns for investment casting are 1) low coefficient of thermal expansion, 2) low thermal conductivity, 3) low compressive strength, 4) low melting or softening point and 5) complete combustion to gaseous products during burn-out. Some of these characteristics minimize the stresses that cause cracking in the ceramic coating during pattern burn-out. During pattern burn-out, the ceramic shell has very low tensile strength and is easily deformed and/or cracked. One printing technique that helps meet these requirements is printing “sparse”, which means that the printed object has a solid surface skin but is hollow inside. Various honeycomb type internal structures can be printed to provide sufficient strength for handling but maximize the collapsibility of the structure during burn-out, thus allowing the structure to collapse onto itself rather than creating tensile stresses in the ceramic shell.

The additive manufacturing processes described in this paper are 1) binder jetting technology to fabricate (i) sand molds and (ii) expendable patterns for investment casting and 2) fused filament fabrication and vat photopolymerization to produce expendable patterns for investment casting. All of these processes allow the economical manufacture of cast structures that are impossible to mold using conventional methods.

Production of Sand Molds and Expendable Patterns for Investment Casting Using Binder Jetting Technology

One form of 3D printing spreads a layer of uniform thickness of particulate material on a moveable platen, binder is jetted where desired to cause bonding of the particulate material within the layer and to the underlying layer, a new layer is then spread, and the process repeated until the desired shape is complete [2-5]. The particulate material can be a polymer coated refractory material, such as gypsum or silica sand, or a polymer, such as PMMA (polymethylmethacrylate). When the "binder" polymerizes, the particles are bonded together. Examples of this method for producing molds for casting are the ZCast™ direct metal casting process [6] and the ExOne™ process [7]. An example for producing expendable patterns for investment casting is the Voxeljet process [8]. In these processes, molds, cores or expendable patterns are produced on a 3D printer from CAD models. For the ZCast process, the molds and cores require a subsequent curing cycle [9]. ExOne molds and cores do not require subsequent processing.

These technologies allow the casting engineer the flexibility to produce castings that were previously impossible to produce using conventional molding processes that require patterns with draft and parting lines. With 3D printing, neither draft nor parting lines are required. As a matter of fact, backdraft is permissible and features that previously required separate cores can be integrated into the molds. Simply put, almost anything that can be designed mathematically can now be produced as a casting. The primary limitation on these processes is the removal of unbonded sand from the molds and cores. Also, the number of binder/sand systems is limited, but this limitation is being addressed.

Producing a Turner's cube was often a test for new machinists. The machinist had to 1) determine how to produce the desired shape and 2) operate the equipment at the level of expertise necessary to produce the desired shape. A Turner's cube casting was created in CAD and a sand mold was produced by binder jetting. There was an issue with removal of unbonded sand as evidenced by the incomplete fill in several sections. This was a very challenging casting for a group of new casting engineers. The cast Turner's cube is shown in Figure 1.

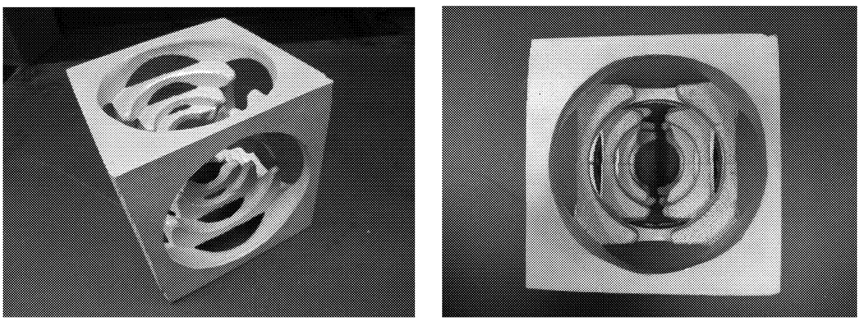
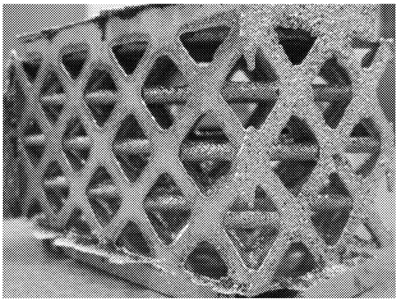


Figure 1. Turner's cube produced from a 3D binder jetted sand mold.

Complex, cellular structure castings cannot be produced by any process other than 3D mold printing. These casting are currently being produced at Virginia Tech using a combination of ordinary chemically bond sand and 3D printed cores. The 3D printed core forms the complex, cellular structure and the ordinary chemically bond sand forms the remainder of the mold (at low cost). The details of producing the complex, cellular structure castings has been discussed in detail elsewhere [9-11]. These castings have been produced in ferrous (iron & steel) and non-ferrous alloys. Complex, cellular structure castings are shown in Figure 2.



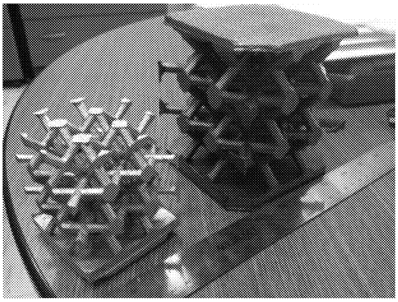
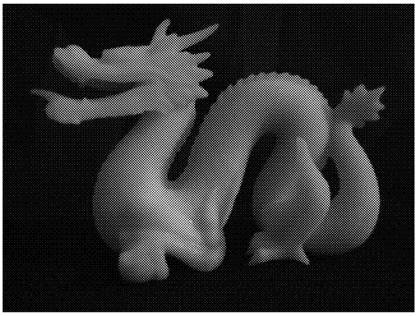


Figure 2. Complex, cellular structure castings produced from 3D binder jetted sand molds.

The mechanical properties of the complex, cellular structure castings shown in Figure 2 are currently under investigation. Modeling has indicated that the energy absorbing/dissipating properties of these structures under blast conditions should be exceptional. These castings are multi-functional structures and their use is only limited by the imagination of the designer. Examples of potential uses for cellular structure castings are 1) blast resistant panels for armored vehicles, 2) blast & fire resistant doors, bulkheads or walls on ships, 3) lightweight elevator floors for high load applications, 4) heat resistant surfaces for vertical take-off and landing aircraft if combined with water or air cooling or 5) a network structure to enhance the structural integrity of protective or ablative coatings.

PMMA is an excellent material for producing expendable patterns for investment casting. Bonded PPMA has very low pattern expansion and produces very low residual ash during burn-out [8]. The only negative for PMMA is that it is somewhat brittle so the expendable patterns need to be handled carefully. Due to the desirable physical properties of PMMA, normal investment casting shell thicknesses can be used successfully. An example of a binder jetted PMMA expendable pattern and the resulting investment casting is shown in Figure 3.



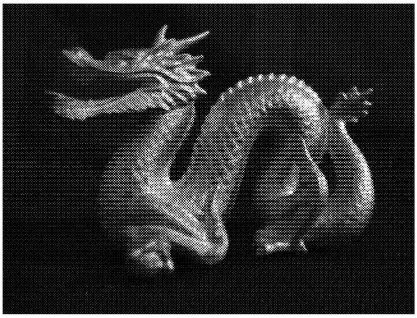


Figure 3. PMMA polymer, 3D binder jetted, expendable pattern and casting; note the fine details (scales) on the casting.

Fused Filament Fabrication and Vat Photopolymerization for Expendable Patterns

A variety of polymers (nylon, ABS, epoxy resin, etc.) are used in additive manufacturing and some are better than others if the end use is an expendable pattern for investment casting. Fused filament fabrication machines heat a polymer to slightly above their melting point and then force the polymer through a die (extrude the polymer) onto a moveable platen. The extruded polymer is deposited layer by layer until the complete part has been built. An alternative to polymer extrusion is vat polymerization. In this process, a vat of liquid polymer is locally polymerized (turned to solid) using UV light or laser energy. A digital file with surface geometry is sent to the printer which directs the polymerizing energy to the desired locations and layer upon layer of polymer is built on a moveable platen. Scaffolding is built alongside the part to provide support for overhanging structures and internal voids, therefore permitting the ability to produce most any shape. These support structures need to be removed along with any entrapped liquid polymer before use. When printing polymers for expendable patterns, there is also an advantage to making the pattern with the least amount of polymer possible since 1) this reduces cost (less polymer consumed) and 2) this reduces the amount of polymer that must be removed from the mold during burn-out. Printing a shape with a solid skin and a honeycomb internal structure is termed "sparse" printing and is very effective in improving the performance of printed polymer expendable patterns [12].

A truss structure and a turbine wheel with airfoil shaped vanes were investment cast using expendable patterns produced from ABS polymer via fused filament fabrication [13, 14]. These structures cannot be easily or economically produced using conventional molding techniques. These castings could be produced using a two-piece mold plus complex core assemblies, but this would produce parting line flash that would need to be removed and the dimensional accuracy would not be nearly as good due to the fit-up tolerances that would be needed for the molds and cores. Printed ABS polymer expendable patterns were successfully used for these castings but the investment casting shell had to be made 50% thicker to prevent cracking during polymer burnout. A truss structure investment casting and a turbine wheel investment casting produced using polymer extrusion printed expendable patterns are shown in Figures 4 and 5.

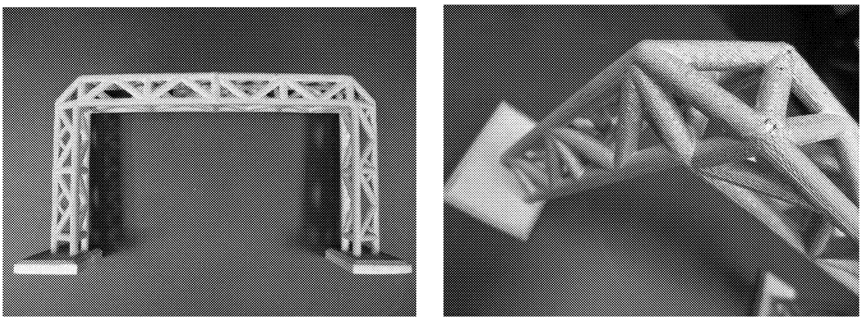


Figure 4. Truss structure produced by investment casting using an ABS polymer, 3D extrusion printed, expendable pattern.

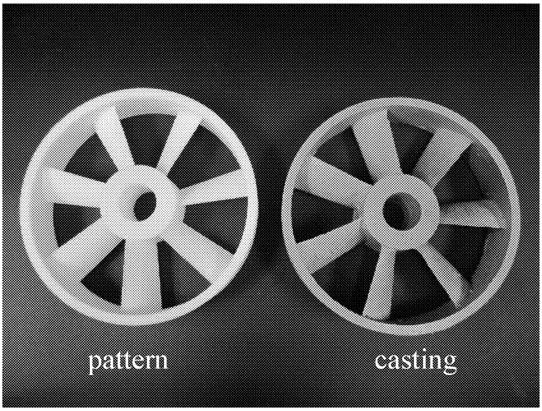


Figure 5. Turbine Wheel: ABS polymer, 3D extrusion printed, expendable pattern and investment casting.

Vat polymerization and sparse printing was used to produce expendable patterns for testing from an epoxy resin containing reactive diluents [15]. Expendable patterns for investment casting have been produced using this process since 1998 [11]. A sphere was investment cast using an expendable pattern produced from vat polymerization. The pattern was "sparse" printed. The internal honeycomb structure was visible in the pattern but only the external steps were apparent on the casting. The pattern and casting are shown in Figure 6.

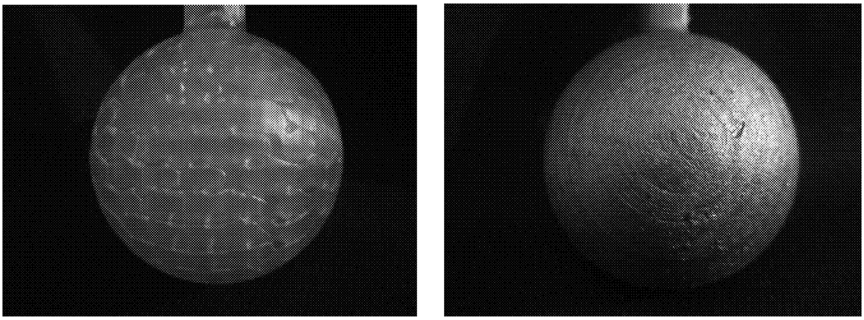


Figure 6. An expendable pattern for a sphere with a "sparse" internal structure produced using vat polymerization. The internal structure was visible in the pattern but only the external steps were apparent on the casting.

Concluding Remarks

Additive manufacturing has demonstrated the ability to transform the casting industry. Numerous additive manufacturing techniques and materials are currently available to make shaped castings available by the next day or within a few days; giving new meaning to fast-to-market.

Acknowledgements

The authors would like to acknowledge ExOne for printing the cellular structure sand cores, Voxeljet for binder jet printing the PMMA dragon pattern and test patterns, the Virginia Tech DREAMS Labs for printing the ABS polymer truss structure, turbine wheel and test specimens via fused filament fabrication, and 3DSystems for producing test specimens using vat photopolymerization. The authors would also like to acknowledge the Virginia Tech alumni and students (Shawn McKinney, Patrick Stockhausen, Ruthie Kay and Shawn Bottoms) who designed, molded, poured and finished the shaped castings highlighted in this paper.

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