ADDITIVELY MANUFACTURED SINGLE-USE MOLDS AND REUSABLE PATTERNS FOR LARGE AUTOMOTIVE AND HYDROELECTRIC COMPONENTS

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Abstract

Additive manufacturing (AM) has the potential to reduce costs in the casting industry, particularly for large parts (i.e., components with any dimension > 12 in.). Here, pilot-scale production case studies of hydroelectric and automotive parts were used to evaluate two AM-enabled casting methods: the direct printing of sand molds by binder jet and printing of reusable cope and drag patterns for sand casting. An additional benefit was found when additively manufactured patterns were used in combination with heat-treat free aluminum alloys, to produce castings of complex hydrodynamic surfaces. These parts previously required production via subtractive machining due to part distortion induced by the quench step of heat treatments. The machine types used for the three case studies are sand-binder jet, high-resolution polymer fused deposition modeling (FDM), and big area additive manufacturing (BAAM) FDM in combination with CNC machining. Each method demonstrated distinct advantages over traditional casting practices in particular use cases. Single-use molds show great reductions in start-up cost to produce one-off or legacy parts, and additively manufactured impression patterns show promise for innovating the tooling design process for complex geometry and large castings.

Keywords: *casting, additive manufacturing, pattern, tooling*

Introduction

Cast parts can be manufactured with a variety of methods including permanent mold (e.g., die casting, gravity, and low-pressure casting) and expendable mold (e.g., sand mold, pattern, and investment casting).[1,2] Permanent mold methods (e.g., die casting) possess high fixed costs prior to initial part production and thus are generally used for applications where a large number (many thousands) of identical parts are required. When smaller production quantities, high performance, or more certain geometries are required, foundries generally utilize expendable mold techniques (e.g., sand, lost foam, and wax).[1,3]

The pattern approach, a process wherein reusable wood or plastic patterns are used as negative impressions to create single-use sand molds, is commonly employed for the production of large and complex parts. Pattern development starts by separating the part's impression into two components, called the "cope" and "drag." The cope images the top/upper geometry of the part and the drag images the bottom/ lower geometry of the part.

Additionally, some castings require complex internal geometry not able to be imaged as a part of the cope or drag. In these cases, a core box is created which is the impression of the part's internal geometry. Once all the mold pieces are produced, they are assembled and the space left empty after joining the two halves will allow molten metal to fill the mold, creating the final part. Patterns are typically produced from a low-cost material (e.g., wood or high-density plastic) by "subtractive" manufacturing techniques: reducing a large block of material to the appropriate shape and size, either by hand or computer-numerical-control (CNC) machine tooling.[3] The necessity for the pattern feedstock to be more massive than the final pattern increases costs for large and complex geometries requiring a significant portion of the initial pattern material to be machined away.[4,5]

This study sought to leverage additive manufacturing (AM) to reduce the cost per unit of cast parts. Two basic processes were identified and evaluated: printing a sand mold directly and printing a reusable pattern from which sand molds can be produced. A cylinder head which was previously produced using traditional casting methods was selected for the printed mold trial. A large transmission casing and hydroelectric turbine components were chosen as trial parts for the pattern approach. This approach permitted the evaluation and comparison of several different printing techniques and part geometries. Previously, the transmission casing was subtractive manufactured from billet with a CNC machine tool, requiring a very long machining time and resulting in wasted material and tool wear. Generally, casting this part would enable lower per unit costs once a production threshold is reached.

The three parts selected for the casting studies are reflective of the aluminum industry's continued expansion into both the automotive and hydroelectric markets.[6–10] Automotive industry adoption of aluminum has steadily risen over the past decades as a result of automotive manufacturers' increased focus on fuel efficiency and lightweighting.[11] Further, distributed hydroelectric power generation is a rapidly growing industry with no universally established material or manufacturing process preferences.[6] Machining parts from billets are possible, but not economical. Cast solutions would be advantageous, but corrosion performance and geometric distortion resulting from heat treatment have limited the use of cast aluminum products for this application.[10] The hydrodynamic blades use a complex blade profile with tight geometric tolerances for achieving high efficiency which is problematic because the distortion produced during heat treatment and quenching of cast products can easily bring the geometry out of tolerance. A recently developed series of aluminum-cerium alloys do not have this limitation because they can be used effectively in the as-cast state[12–14] and are used in this work. If inexpensive processes for prototyping and producing new distributed hydroelectric technologies can be developed further, aluminum casting could become the method of choice for the growing application space.

Case 1: Printing of Single-Use Sand Mold

Many traditional casting processes suffer from high up-front costs to create tooling when compared to the cost of downstream part production. For example, the part in Case 1 is typically produced using die casting, a technology where tooling costs often exceed hundreds of thousands of dollars. In order to prototype, die casting houses will typically adopt gravity-fed casting processes with long lead times and high costs. The biggest investment is the pattern which could be used for hundreds of copies of a single part but is often only used for one or two copies of a prototype before a full redesign must take place, greatly increasing the development costs. This case study looks at the possibility of using 3D-printed sand molds to prototype parts for casting techniques, including die casting. Successful implementation of this technology would create a path for initial prototyping and part changes up to complete redesigns at very low cost when compared to other methods.

The typical tooling process for die casting prototypes either involves rapid prototyping of steel molds for use with a pressure die casting rig or plaster mold prototyping.[1,15–17] Both techniques require long lead times and each places different limitations on the geometries that can be produced in timely and cost-effective manner. Binder jet AM production of sand molds presents lower lead time much more flexible geometry (down to feature sizes of 0.5 mm with certain aspect ratios). Once the design is delivered, lead times can be as short as a single week for multiple prototype molds. Using AM also affords the possibility to test multiple prototype platforms simultaneously, as each mold is printed separately and major or minor changes to one do not affect others. It should be noted that for AM molds produced by binder jet printing, loose sand must be removed from the negative space before casting can proceed. Another benefit is the flexibility inherent in AM technology that affords a single casting house or prototyping firm to produce any geometry of mold for numerous clientele.[4,5,18,19] These attributes combine to make additive manufacturing of single-use molds possibly the most rapid, flexible, and cost-effective means to produce prototype castings.

Once prototyping is completed, mold patterns or dies can be designed for high volume production, as AM technology does not benefit from economies of scale and has linear cost increase with production volume.[5,18,19] As a result, cost and time savings afforded by the printing of molds does not typically scale to widespread part production and is usually advantageous for low quantity specialty parts or prototypes. However, it is likely to be economical even at scale for highly complex geometries that benefit from the inherent flexibility of AM.

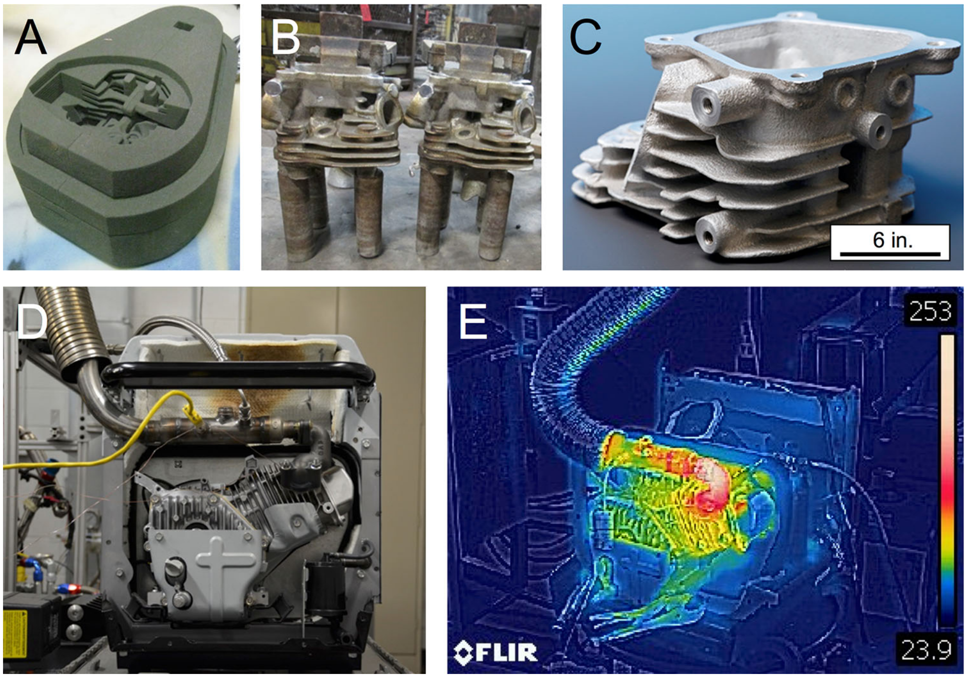

Figure 1. (a) Additively manufactured sand mold, engine head after (b) casting and removal of mold and (c) gating removal and sand blasting, (d) assembled engine, and (e) thermal image of engine in operation.

Figure 1 illustrates mold production, cast and finished part, and engine assembly. Prior to printing the mold, Magma®, a casting simulation suite used to optimize the casting performance via cooling rate models, was used to predict and analyze the part's solidification behavior. Variations in solidification rate are particularly concerning in large parts as they can result in undesirable material defects, such as macroscopic porosity and macrosegregation of solute elements. Additionally, lack of cooling control can lead to incomplete mold filling. Based on this model, features promoting optimized cooling rates were then added to the mold design. Once the design was finalized, a single-use sand mold was manufactured from a sand and binder mixture using an ExOne Max machine by a binder jetting technique (Figure 1a). The mold was then coated with a zircon-based mold wash to ensure no sand/metal interaction and a good surface finish of the part following the casting process. Molten aluminum was poured into the mold and, following solidification, the part was removed from the sand mold by mechanical knock out (Figure 1b). The part was then sand blasted to smooth the surface finish (Figure 1c), installed on a single cylinder engine (Figure 1d). The engine survived a full load test operation and thermal imaging confirmed that the engine head was operating within expected thermal ranges (Figure 1e).

This design, optimization, mold printing, and cast production methodology proved successful for the production of single-run or low production volume components by eliminating the high initial cost barrier typical of casting production methods and lowering part production lead time in the case of legacy parts which may be mission critical.

Case 2: Production of Reusable Patterns via High Resolution Polymer FDM

A second method for applying additive manufacturing techniques to aluminum foundry tooling is to print the impression pattern used to make the sand molds for sand casting. Printed patterns can be used multiple times, combining economies of scale with the time, material, and cost savings enabled by AM. In this example, a pattern was designed to create the mold for a transmission casing for a newly distributed kinetic hydroelectric technology which has since reached the commercial deployment stage. The previous production method for this part required subtractive manufacturing (direct machining from billet) resulting in significant material waste and limited geometric complexity. In this traditional approach, costs increase with part complexity due to additional machining time and labor costs to position parts in the machine, supervise machine performance, and make adjustments.[4] Conversely, AM requires less time to print complex geometries because instead of removing material to create features, features are produced in their final geometry and no supervision of printing is required. In fact, the parts outlined below were printed over a holiday weekend with no supervision and were removed the following week, resulting in one-tenth the labor cost when compared to traditional subtractive methods. The end user's goal was to reduce final part weight by designing "cutouts" in non-structural areas of the part. In traditional methods, cutout would require additional machining time but including them reduced build time in AM. AM also allows more flexibility in pattern design by avoiding position limitations inherent in CNC machining processes.[4] The summation of these benefits means that as part complexity increases, more value is captured by additive manufacturing for reusable patterns.

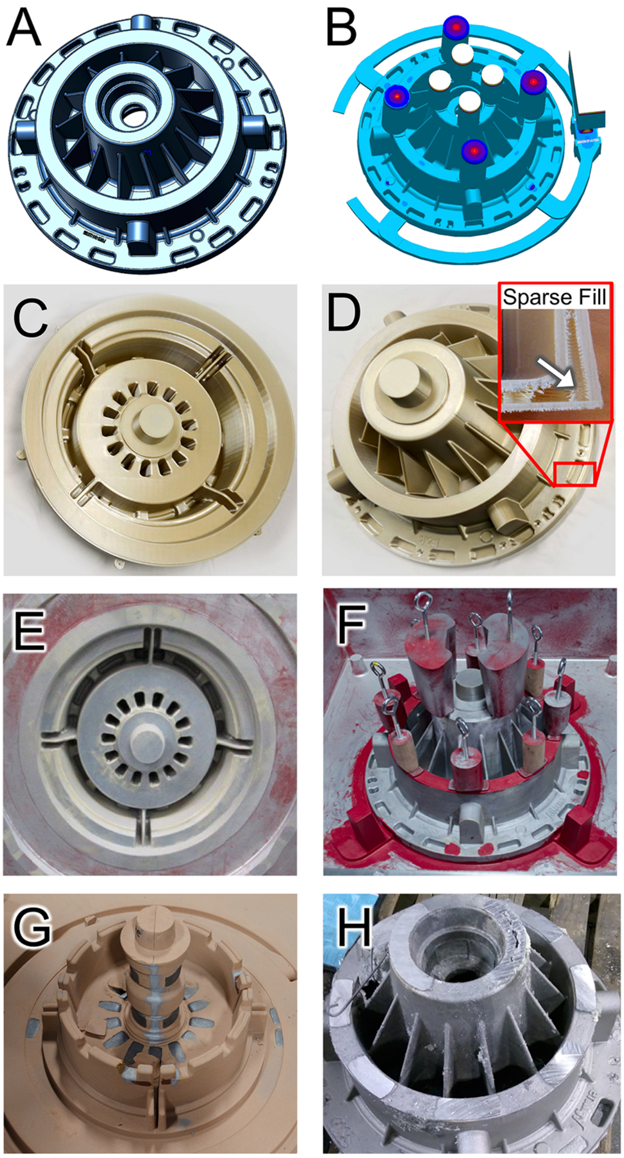

Figure 2. (a) Render of original part design, (b) solidification modeling predicting complete filling, (c) AM cope pattern, (d) AM drag pattern with a cross section of pattern showing sparse-fill print method, (e) mounted cope pattern with mold release applied, (f) mounted drag pattern with cooling features installed, (g) sand mold of internal features resulting from cope plus manufactured core box pattern, and (h) final cast part with risers removed.

The first steps, similar to traditional pattern production methods, involve designing patterns to the desired part specifications. Unlike subtractive methods, casting approaches require features that promote the flow of molten metal in the mold and that control the solidification rate. Figure 2a shows the model of the first part designed for production using this method. Casting predictions and optimization of the part were modeled using Magma® software. Results of the modeling (Figure 2b) were used to determine placement of chills (small heat-conducting rods or blocks) and other devices needed to accelerate or retard local cooling rates. These features were added to the pattern using traditional methods and materials prior to filling with sand. Gates and risers, additional fill volumes used to enhance mold filling for optimal solidification, were printed separately from the part pattern. Though not exclusive to AM approaches, producing gates and risers separately from the main pattern is advantageous, as they can be quickly adapted and swapped for new material selections with different thermodynamic properties without the need to fully rebuild the pattern. For this particular part, the complexity required separate imaging the geometry of the interior portions of the part, so a core box pattern was also printed (visible in the center of the mold in Figure 2g). Since the cope and drag patterns each only imaged half of the part, they could be easily printed without support, realizing additional time and feedstock savings. Figure 2c, d shows photographs of the completed pattern printed on a Stratasys Fortus 900mc fused deposition modeling (FDM) system; this printer's build envelope 36″ × 24″ × 36″, suitable for the large part demonstrated in this study (23.2 in. in diameter and 11.7 in. tall). ULTEM (amorphous thermoplastic polyetherimide resin), a material which combines high-dimensional resolution with suitable mechanical properties, was selected as the print feedstock since rigid material was required to prevent cracking and bending when sand is poured and compacted on top of the pattern. An additional benefit of using ULTEM is the good final surface finish, meaning no supplemental sanding or machining would be required. A nozzle diameter of 0.01 in. and layer height of 0.0005 in. was used. The inset of Figure 2d illustrates the printing strategy used for producing the finished pattern. Termed "sparse fill", this method drastically increases the printing speed and reduces material use/cost. A central volume fill of approximately 2% was used for support during printing, resulting in an outer "skin" of the part of approximately 0.1 in. thick. The sparse-fill approach required 84 h of print time and 260 in.^{3} of material. Alternatively, printing a solid cope pattern would have required 467 h and 1664 in.^{3} of material. The sparse-fill approach represents print time and material reductions of 82% and 85%, respectively, when compared to printing a solid part.

The print system was optimized by producing small test sections with variable print direction, fill volume, wall thickness, and internal support, after which a judgement was made on material fill ratio and strategy. Once printed, the cope, drag, core patterns, additional gating, and chills were assembled and installed in a mold box without the need for additional machining. The pattern and mold box were painted, and a mold-release agent was applied for easing pattern removal. ULTEM material does not present a reactivity concern with traditional mold-release agents, an important consideration when selecting a printing material.

Following an inspection of the assembled patterns (Figure 2e, f), sand and binder mixture was poured around the pattern forming the cope and drag molds. Following a sufficient cure time, the sand mold was manually removed from the pattern. During removal of the cope mold, the pattern attachment points failed and the pattern separated from the mold box remaining attached to the cope portion of the mold. It was concluded from the analysis that the sparse-fill construction led to lower material strength near the attachment points. The stresses at the connection points were too great for the sparse-filled material to withstand, resulting in failure. To correct this deficiency, epoxy was added in the sparse-fill void space near the connection points. The pattern was then remounted in the mold box. In future patterns, sparse-fill build ratios could be reduced or suspended near known mold box attachment points to increase pattern strength and prevent separation. Once the pattern was remounted, the sand-binder mixture was repoured onto the pattern to create the sand mold. Once the mold was successfully extracted, the core was installed to complete the cope (Figure 2g).

In designing these molds, the shape flexibility of AM techniques was prioritized over optimizing sand/pattern interactions, and as a result, when the mold was removed following sufficient cure time, some sand remained attached to the pattern. This effect is a common problem with complex pattern designs. Generally, pattern makers limit the overall feature depth and feature depth to width ratio.[20] This design methodology was not used here; instead, the mold was designed to test the limits of additive manufacturing as a system for the production of sand mold patterns. Although ULTEM produced a good surface finish, areas with high depth to width ratios showed elevated surface roughness values due to the presence of layer-to-layer stepping. This mild roughness combined with the mentioned feature depths resulted in the observed local issues with sand-pattern separation. To correct this, some pattern surfaces identified as problem areas were smoothed manually. These modifications resulted in satisfactory mold/pattern separation for end-user needs. The potential need for smoothing of patterns is an important aspect that should be considered during ramp-up for industrial adoption. After final mold assembly, the part was cast with an Al–8 wt.%Ce–10 wt.%Mg alloy. The final complete part can be seen in Figure 2h.

It was important for the viability of the printed pattern production method to confirm the reusability of the patterns after successful part production. As such, the patterns were inspected after the first part had been cast. The only notable wear which would not have been expected with traditional wooden molds was a higher amount of surface smoothing from the abrasive nature of the sand. This, however, would lead to mold to reach peak performance as it is used, leading to better mold-pattern separation and easier coating. Overall, the pattern was deemed structurally sound enough for many more mold production runs.

This case study shows the compatibility of printed patterns with traditional casting foundry practices. Both lead time and cost are reduced when compared with standard subtractive production practices (Table 1). The combination of lower cost, near-drop-in compatibility, and reusability makes the AM production of molds an intriguing path forward for innovation in the centuries-old casting industry.

Case 3: High Throughput Production of AM Patterns Using BAAM FDM

Case 2, which used a printed pattern to produce a transmission casing, demonstrated the feasibility of an AM pattern for use in complex part production. To accomplish additional cost reduction and enable larger-scale production, a different polymer printing method was evaluated in Case 3 for the potential to further reduce costs. Big area additive manufacturing (BAAM) is a high throughput, large build volume FDM system,[21] and parts produced on BAAM hold the world record for largest additively manufactured parts.[22] The BAAM system, though much faster than the Stratasys system, is not suited to the printing detailed complex and high-resolution geometries like those

Table 1. Case 2 Cost Comparison—High Precision, Complex Pattern

	Conventional pattern (quote)	AM pattern (actual)
Build/print cost (time)	$14,820 (228 h)	$12,610 (194 h)
Pattern rigging cost (time)	$4550 (70 h)	$2600 (40 h)
Material cost	$2000	$4700
Total cost	$21,370	$19,910

of the transmission case. For comparison, the Stratasys Fortus has a minimum build layer thickness of 0.020 in., while BAAM's is 0.160 in., and ULTEM has higher part design flexibility than the chopped carbon fiber ABS used in the BAAM system.[23,24] These factors led the team to focus on using BAAM to produce the pattern for blades and spokes for hydroelectric energy production that required limited geometric complexity but close design tolerances.

BAAM printed each pattern and its mounting plate (Figure 3a) in approximately 4 h and printed multiple patterns in parallel. Printing the pattern and mounting plate together reduced the time associated with pattern mount optimization and lowered overall cost. Overall, the BAAM approach reduced the time for pattern production by approximately 90%. Because the printing process and material do not have the inherent surface smoothness of the process in Case 2, the patterns required machining and manual smoothing to reduce surface roughness prior to use. Machining was done using a Thermwood machine and added approximately 4 h to pattern production time. The additional machining time was reduced by taking appropriate steps such as adding fiducial marks and making sure that the pattern box plane could be easily reached by the CNC by not printing the box sides. The end user of this part (EMRGY inc, a company producing distributed hydroelectric turbines) immediately moved the process into full-scale production, in which pattern boxes were mounted (Figure 3b, c) and sand molds produced (Figure 3d). Pattern boxes were approximately 3 ft × 6 f × 1.5 ft tall. One of the cast turbine spokes after removal of the risers is shown in Figure 3e before final machining in preparation for assembly. As previously stated, the aluminum alloy chosen for the turbine spokes and blades needed to be used in the as-cast condition to preserve the designed geometry produced by the AM molds and avoid warping during heat treatment. This was achieved by producing the part out a newly designed castable Al–8 wt.%Ce–10 wt.%Mg alloy[12–14] that forms a fine distribution of intermetallic eutectic phases during solidification (Figure 3f, g) and has a high Mg content for solid solution strengthening. The high as-cast strength can be contrasted with most commercial aluminum alloys that form their strengthening phases during heat treatments. The ability to take the prototype pattern design and move directly to production with minimal lead time is a key advantage of using additive manufacturing to produce patterns for casting. Like the patterns from Case 2, these patterns were inspected between mold production runs and showed good resilience

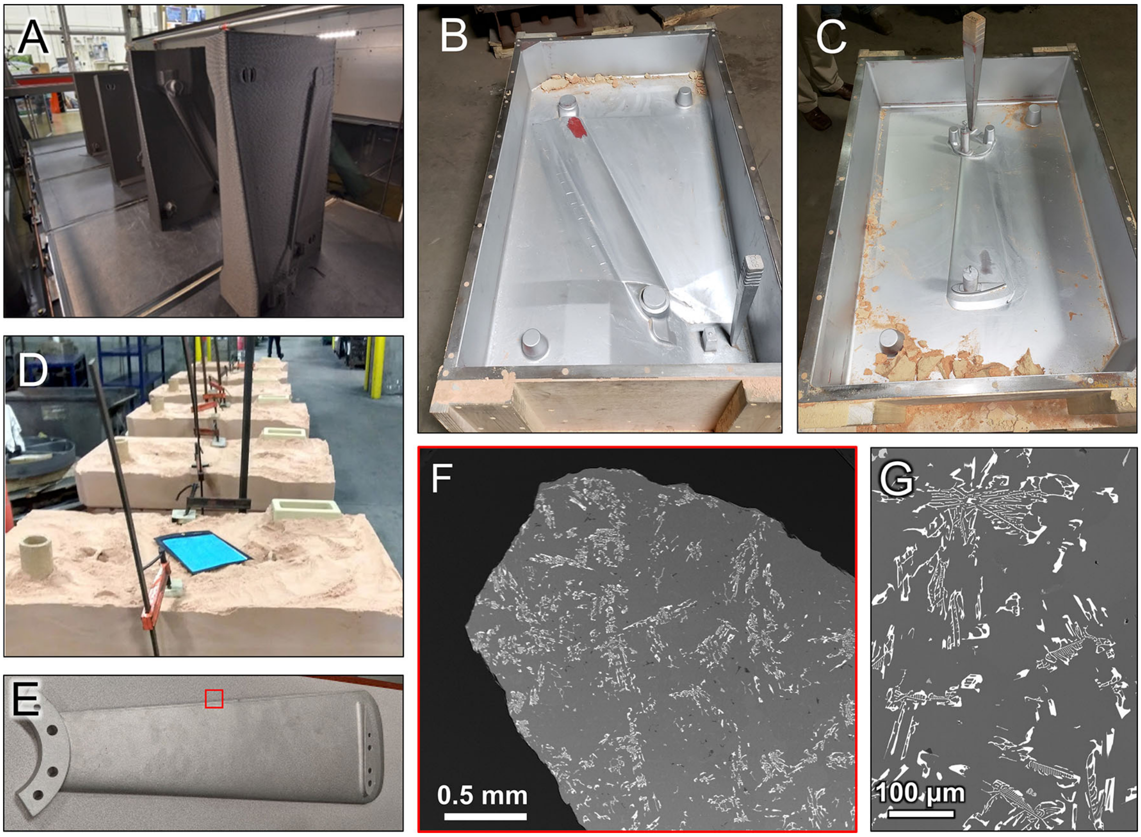

Figure 3. (a) Blade pattern cope and drag being printed on BAAM build bed. Finished, mounted, and coated cope pattern box of (b) blade and (c) spoke design. (d) Sand molds produced from printed patterns awaiting filling with molten aluminum. (e) Cast spoke after the removal of risers and grit blasting. (f, g) SEM micrographs from the trailing edge of the spoke.

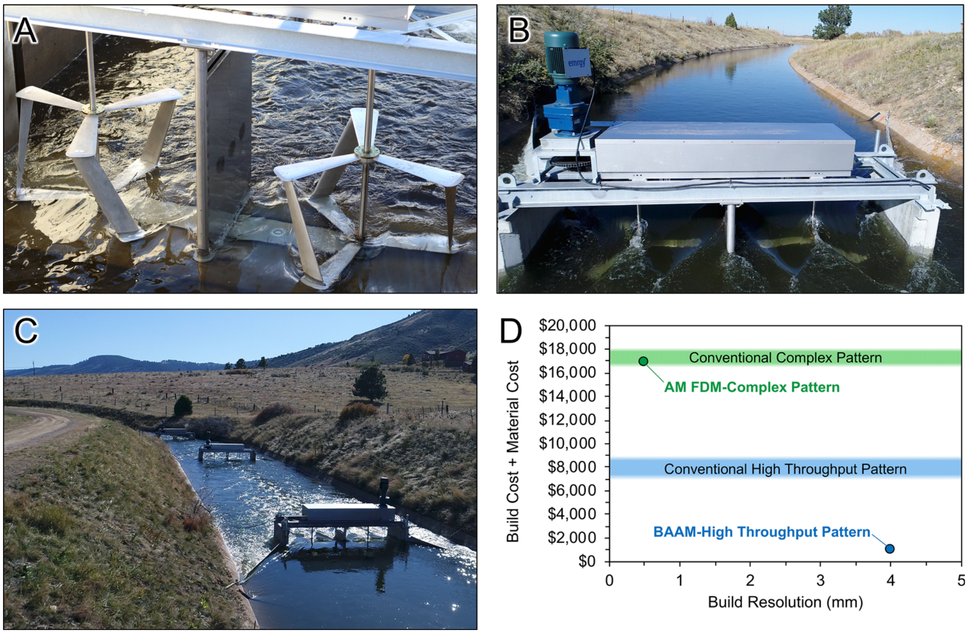

Figure 4. (a) Blade assemblies produced from printed patterns installed on EMRGY Inc. distributed hydroelectric system. (b, c) Multiple EMRGY turbines operating at capacity with parts produced from complex and high throughput AM patterns. (d) Build cost + material cost versus build resolution for the materials in this study, based on Tables 1 and 2

Table 2. Case 3 Cost Comparison—High Throughput Pattern

	Conventional pattern (quote)	AM pattern (actual)
Build/print cost (time)	$5600	$260 (4 h printing) $260 (4 h machining)
Pattern rigging cost (time)	$3300	$5130 (80 h)
Material cost	$2000	$400
Total cost	$10,900	$6050

to the process of mold production. Parts from Case 2 and Case 3 were installed successfully in a commercialized device by the end user. The turbine blade assemblies are currently being used in US artificial waterways, as seen in Figure 4a–c.

By using parts manufactured with the AM molds, the original equipment manufacturer was able to meet strict customer lead time requirements and cost reduction for the commercialized device. The blade design was not finalized until after the customer contract was awarded, and the team was able to complete the design, mold construction, blade manufacturing with the BAAM process, and the first article delivery within 90 days. In addition, the total cost per blade paid by the end user was 80% lower than the subtractive manufacturing technique that had been used previously. These significant lead time and cost reductions are particularly beneficial for small companies that seek to commercialize and grow quickly. In addition, the AM molds are of sufficient quality to be used for at least 100 commercial devices, which makes this process an attractive investment for companies seeking to achieve low quantity beta production of new product designs.

Comparison of Printed Patterns to Traditional Methods

AM patterns have the potential to reduce production cost and time for complex and/or large castings (i.e., parts with dimensions of approximately 12 in. or greater). This study demonstrates that for small quantity or large part manufacturing, the higher material cost of AM methods is offset by savings in labor costs and CNC machine time for complex parts, making AM competitive for industrial-scale sand casting. Tables 1 and 2 compare the cost and production time between the AM approaches and quoted cost and timeline for a traditional pattern. Cost figures are calculated using a machine cost of $65 per hour, which is based on quoted costs from pattern vendors.

A comparison of (material + build cost) versus build resolution for the case studies here is presented in Figure 4d. For highly complex patterns (e.g., Case 2), the cost of AM pattern production is already very similar to conventional methods. As AM technologies become more widespread, material and print costs are expected to further decrease, making this a viable upgrade to existing methods. The BAAM approach presents a more complex picture. As a first-of-its-kind manufacturing process, rigging time (i.e., manufacture of the mold box and time to mount patterns into boxes) was very high. The inability to post-machine an integral mold box using the available tooling for the CNC machining system was the limitation, not any inherent limitations to the BAAM system itself. Over time, these costs are expected to reduce making the BAAM method even less costly when compared with traditional methods. However, while the use of BAAM has the potential to dramatically reduce cost, the lack of design complexity afforded by this method reduces its possible use cases when compared to method outlined in Case 2.

Due to the wide disparities between die casting and direct binder jetting of sand molds, cost comparison for Case 1 was deemed to be not meaningful. It should be noted though, that the cost to produce this mold was <$1000, several orders of magnitude less than the cost of a die casting mold to produce the same component.

Despite the relative immaturity of AM mold-pattern production, when properly leveraged in foundry environments, the AM approach saved both time and cost for the production of low volume, geometrically complex, and large parts. When compared to traditional manufacturing methods requiring labor-intensive subtractive methods and constant supervision, AM is a fully automated process resulting in a smooth surface finish, reducing labor costs, and eliminating pattern smoothing steps. The automated nature of mold and pattern printing means that as process knowledge grows, and print pathways become more well understood, cost is expected to be further reduced.

Outlook

This study demonstrated the utility of using AM to produce molds and patterns for complex sand cast parts. Further analysis of the economic viability of this approach is required, especially since the number of cycles each pattern may be used is unknown. This case study also did not analyze what production quantity would be required to offset the investment costs for a Stratasys FDM or BAAM FDM system.

Additionally, the use of alternative resins and polymers in the AM process could reduce material cost and build time for pattern production. Polymer selection may be limited, however, to compounds that will not react with either the mold-release compound or the sand mold binder. Alternative materials and printing methods must also balance increased print speed with degradation in surface finish, since a rough finish will further complicate mold/pattern separation when producing sand molds. One potential benefit of AM pattern production would be quick dissemination of patterns to multiple foundries, potentially streamlining production start-up dramatically.

Conclusion

AM is a technically viable option for large pattern printing and is particularly well suited for complex part geometries. Additional material costs of the AM approach are offset by savings in machine/labor costs for pattern production. The use of less expensive resins and/or AM machines capable of reducing print times have the potential to further increase the economic advantage of AM over traditional pattern production techniques and offset the high fixed costs of AM. Direct printing of sand molds expands casting applications to more complex part geometries but has limited applicability for large production volume parts. The use of AM patterns combines the geometric flexibility of AM with cost savings as multiple parts are produced with a single pattern. The automation of mold and pattern production made possible by AM technologies also ensures reduced cost as the AM market grows more diverse and cost competitive. Labor-intensive mold and pattern creation date back millennia, but the widening availability and diversity of AM technology present new opportunities for innovation and cost savings in this area of foundry processes.

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