ORNL/TM-2023/3051
CRADA/NFE-20-08123

Prototyping and Manufacturing of Magnetic Gearbox Components using Innovations in Castings

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August 22st, 2023

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ORNL/TM-2023/3051

Advanced Manufacturing Office and Water Power Technologies Office

PROTOTYPING AND MANUFACTURING OF MAGNETIC GEARBOX COMPONENTS USING INNOVATIONS IN CASTINGS

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August 2023

Prepared by
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for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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ABSTRACT

In a previous collaboration with Emrgy (CRADA agreement NFE-17-06532), a housing component of Emrgy's 10 kW gearbox was casted out of aluminum alloys using impression molds prepared using 3D printed techniques. (Henderson, 2018). After comparison with Emrgy's existing hardware and material testing, the 3D printed impression molds were verified to represent a valid approach to advance technology readiness and commercialize Emrgy's technology.

The current work targeted complex, larger components for Emrgy's 100 kW gearbox that ultimately have been produced using specially selected and designed printed sand molds. The 3D printed mold techniques (from Phase 1 and Phase 2) represent a strategy to effectively employ additive manufacturing for providing reliable progression of technology readiness level for companies, leading to consistent small, medium, and large scale production. In this collaboration, Emrgy and ORNL determined the most effective mold strategy for one-off prototyping and have successfully cast prototype components using the Al-Ce-Si alloy developed within the Critical Materials Institute (DE-AC05-00OR22725) by researchers here at ORNL. A comparison of mold strategies and their scalability will be discussed.

1. 3D PRINTED MOLD STRATEGIES FOR RAPID PROTOTYPE METAL CASTING

1.1 BACKGROUND

Emrgy, founded in 2014, works to develop flexible, modular hydropower solutions. Emrgy's technology enables customers to tap into unused energy resources in existing water flows to offset grid power consumption and/or achieve grid power independence. They are developing innovative, cost-effective hydropower turbines that combine modular hydrofoils with a proprietary magnetic gearbox-based powertrain in a modular and scalable form factor. This system requires orders of magnitude lower investment cost than other hydropower and can flexibly operate at a range of power capacities, representing a breakthrough in hydrokinetic power conversion.

In Phase 1 of this program (CRADA agreement NFE-17-06532) (Rios, 2018), a housing component of Emrgy's 10 kW gearbox was cast out of aluminum alloys using impression molds prepared using 3D printed techniques. After comparison with their existing hardware and material testing, the 3D printed impression molds were verified to represent a valid approach to advance technology readiness and commercialize Emrgy's technology.

3D printed impression molds provide an affordable option for medium level manufacturing as these molds can be used to makes 10s to 100s of sand molds. An additional prototyping option is 3D printed sands molds which can be even cheaper to manufacture particularly when dealing with one-off parts where a reusable impression mold is not necessarily needed (e.g. proof-of-concept, unavailable legacy component). These 3D printed molds (FDM impression and 3D printed sand) embody a strategy of providing templates and examples of Technology Readiness Level (TRL) progression for companies when additive manufacturing (AM) techniques are effectively employed, incentivizing consistent multi-scale deployment and production. In this collaboration, ORNL and Emrgy produced prototype components using the Al-Ce-Mg alloy developed by ORNL.

Emrgy's 100 kW gearbox (Figure 1) is approximately 1.1 meters in diameter and 1.7 meters long. Emrgy's team has identified approximately 10 components (including housings) in each gearbox that are prime candidates for casting as opposed to other fabrication techniques. The prototyping process has been very expensive for them, and alternatives have included traditional sand casting (>$500,000 for tooling 10 parts) or machining from billet (>$200,000 per part one-time expense). We show that additive manufacturing can accelerate prototype development and can be used in mid-volume production of near net shape cast components.

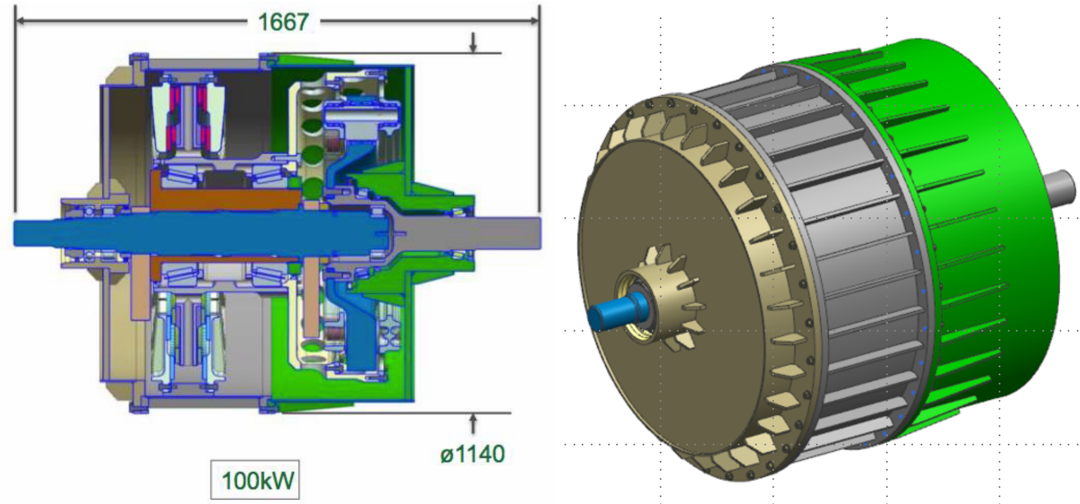

Figure 1. Schematics of Emrgy's 100 kW gearbox (dimensions in mm).

In addition to the exorbitant cost, lead times for both conventional options are lengthy due to the size of castings, so this functionally prohibits multiple design iterations. Given current options, Emrgy cannot afford many design modifications or improvements to its design given the capital-intensive nature of manufacturing. This also limits them from improving the TRL of the gearbox.

Prototyping and manufacturing Emrgy's components with ORNL via 3D printing molds and a Al-Si-Ce (7wt%Si – 2wt%Ce) alloy for casting catalyzes commercialization of Emrgy's product as well as allows them to advance the TRL and performance of its technology using new methods. 3D printed molds can enable short design and testing development cycles, enabling rapid progression to a higher TRL.

This work helps to enable Emrgy to effectively prototype, commercialize, and manufacture its magnetic gearboxes using new processes and materials that result in high performance and accelerated technology development. These attributes contribute to the production of clean electricity at a lower levelized cost of energy (LCOE), which enhances the business case for development of new hydropower resources in the United States. Based on results of Phase 1, it is expected that 3D printing molds will be a viable method to produce low-to-medium production parts with a target of approximately one thousand parts casted per 3D mold (in the case of impression molds).

The success of this program helps Emrgy prove that energy from hydro resources can be cost effectively extracted and converted into reliable electric power using modular, flexible components such as the gearboxes described in this project, leading to expedited commercialization and clean energy generation.

In this Phase 2 work, larger components for Emrgy's 100 kW gearbox have been produced using a 3D printing process (3D printed sand molds), expanding the applicability of printed molds to include complex, high impact components. Lessons learned from Phase 1 have been applied on larger and more complex geometries. A series of five internal mechanical components and three large housing components have been selected as candidates and were reviewed for compatibility with cast technologies using solid modeling and solidification modeling. It was determined that both FDM impression and 3D printed sand mold were preferable options, over conventional methods, for production of Emrgy's components, but due to the cost and one-off nature of this prototyping process, 3D printed sand molds were selected. All 5 mechanical components were sand cast using 3D printed molds and then machined into functional components for testing in a prototype gearbox. The housings were modeled, though casting these components was beyond the budget scope of the current work.

1.2 TECHNICAL RESULTS

1.2.1 Part Identification and Initial Down Selection

Emrgy and ORNL identified more than ten components that could be candidates for casting. Of these, eight were down selected for evaluation at ORNL for feasibility of casting using one or both AM methods (impression or sand molds). Five of these were large internal components that had a mechanical functionality and three were quite large housing components (size can be inferred from schematics in Figure 1). Table 1 is a list of the part type and names as they will be referred to for the remainder of the report. Figure 2 is a machine drawing for the rotor, part SH020, and this is shown here to demonstrate the size and complexity of just one of the components under evaluation. Due to the significant size of the components (up to 1.1 m in diameter) and the one-off parts needed for the prototype performance demonstration, a cost evaluation approach was deemed necessary for the two AM methods. Guided by the cost evaluation (details outlined in section 1.2.2), a second down selection of parts was needed based on the project budget.

Table 1. Parts list evaluated for AM mold/casting feasibility.

Part Type	Part Name
Input Drive Flange	**SH001**
Input Drive Ring 2	**SH002**
Input Drive Ring 1	**SH003**
Rotor Drive Flange	**SH010**
Rotor	**SH020**
Housing	W000
Housing	W001
Housing	W002

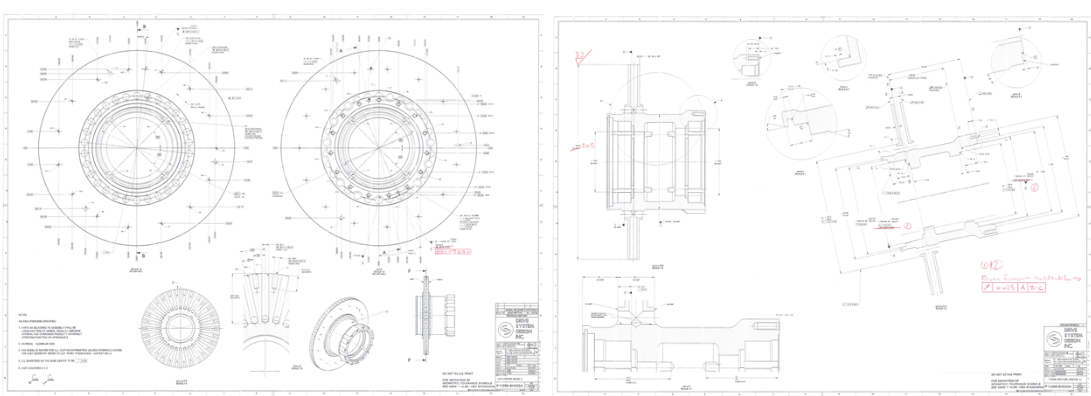

Figure 2. Machine drawing of the rotor, part SH020, which is part of the magnetic assembly of the gearbox.

1.2.2 FDM Impressions and 3D Printed Sand Mold Feasibility and Cost Evaluation

Two AM methods were evaluated from a cost and feasibility standpoint for the 8 identified components: 1) FDM of the positive component shape (impression) for creating a conventional sand mold, and 2) 3D printed sand molds. The primary benefits of FDM are that it is significantly cheaper (up to an order of magnitude) to fabricate compared with conventional subtraction-based fabrication methods and, like conventional impression molds, it can be used to make a large number of sand molds (100s or more). These benefits make this method an attractive option for low- through high-volume manufacturing and could be a viable option for prototyping based on the relative low cost. 3D printed sand molds, on the other hand, are a single use mold, which limits their overall scalability in manufacturing. However, in the case of prototyping, a major cost investment into impression molds could be untenable considering they may become obsolete after a single use if design modifications are necessary. This is one particular case where 3D printed sand molds can find a niche. Based on our evaluation, 3D printed sand molds are the cost-effective option when producing three or less components of a single geometry. The following is a description of the feasibility and cost evaluation.

1.2.2.1 FDM Impressions

In Phase 1 of this effort, FDM impressions were 3D printed at the Manufacturing Demonstration Facility (MDF) at ORNL. This resulted in an estimated 4-fold decrease in cost for the target component compared to the cost of conventional subtraction methods. The FDM approach was compared against the 3D printed sand approach for prototyping cost effectiveness. A detailed description of FDM impressions can be found in the Final CRADA Report for Phase 1 (NFE-17-06532).

1.2.2.2 3D Printed Sand Molds

Sand mold casting is one of the most cost-effective methods for manufacturing components that have a relatively low total number of produced parts. In cases where large parts are being tested, optimized, and design changes are made, sand molds can still be an expensive part of the prototyping process. In sand molds, reusable impression patterns that consists of the “cope” and the “drag” are designed to shape compressed sand to match the outer surface of any given part. The cope and drag have a limited but reasonable lifespan; regularly they have a high cost and produce a decent amount of waste material due to being created in a subtractive machining process. Cost savings have been demonstrated on mid-size (< 45kg) casting by using additive manufacturing of high temperature polymers for this construction of the cope and drag (Phase 1). Some limitations occur when scaled to larger castings. Higher costs can be induced due to machine time, limited build volumes, limited resolution scales, and increased CAD modeling time. All of these make the development of large part volume molds using other AM techniques like sand-printing more prevalent. To minimize costs, additively manufactured sand-molds can be used to decrease the overall cost of making prototyped metal castings. Instead of developing a cope and a drag, the part’s void is directly printed out of sand. The void is modeled after a component geometry (Figure 3A) with some modifications to account for machining the final part to tolerance. 3D sand printing can run into some of the same limitations as polymer printing of impressions, but these can be mitigated with some additional mold design steps. For example, other necessary features of the molds (i.e., gates and risers) are usually manually placed in a conventional sand mold, incurring additional mold preparation time and costs, but these features can be incorporated in the 3D printed sand mold. This reduces effort on the casting foundry floor and accounts for a minimal increase in printing costs.

Cost for printing is usually related to machine operation time and the volume of sand and resin printed. For very large castings wherein the mold cannot be printed in a single part, AM of sand can be used to split the parts into multiple molds which can then be assembled prior to casting.

In this work, 5 large castings for a magnetic gearbox were selected for mold design work. To optimize for larger molds, topological optimization was integrated into the mold designs to limit material and machine time costs. For each part, sand is set to be printed a fixed distance of 7.62 cm from the surface of the part. The part itself is not printed in sand, but a void is created for molten metal to fill as seen in Figure 3C. The fixed printed sand distance gives enough mass to have consistent heat dissipation during initial solidification in the different thickness of the mold. Also seen in Figures 3 and 4 is the splitting of large parts into multiple printed sections. Splitting molds into multiple prints allows for more control over riser placements in the final sand mold configuration and reduces the lost value during print failures in AM prototyping. This process was repeated for a total of five magnetic gearbox parts as seen in Figures 3 and 4.

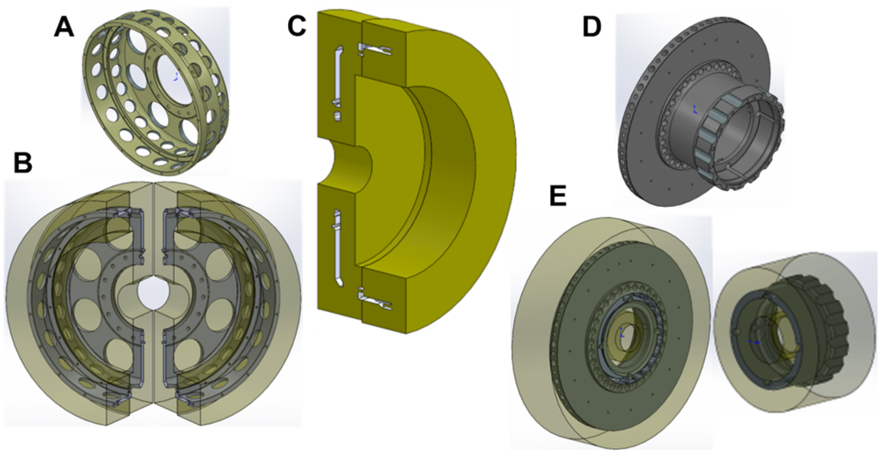

Figure 3. A) Cage for the 100kW magnetic gearbox and the B) topologically optimized sand printed mold for the part. C) The cross section of the four-part mold showing the mold void. D) Rotor for the magnetic gearbox and E) the topologically optimized sand printed mold for the two-part rotor mold.

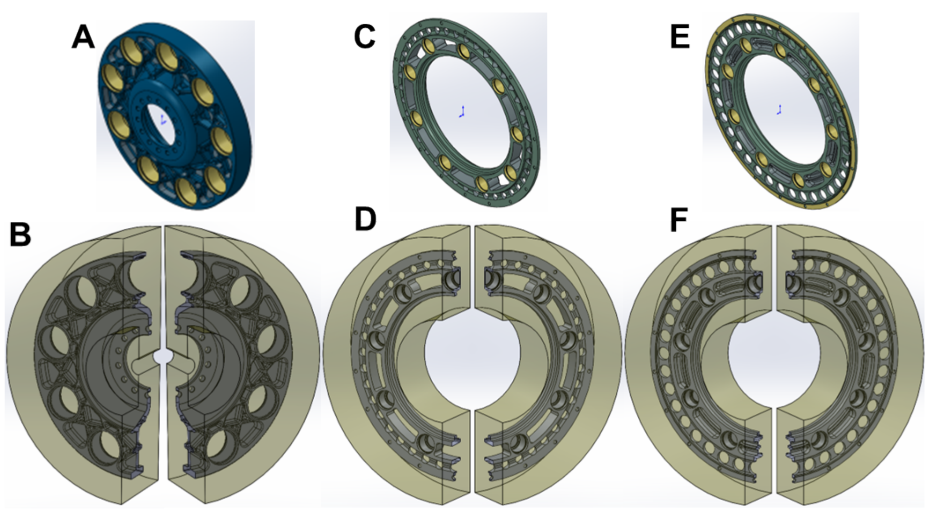

Figure 4. A) Input flange for the 100kW magnetic gearbox and the B) topologically optimized sand printed mold for the flange. C) Input drive ring for the 100kW magnetic gearbox and the D) topologically optimized sand printed mold for the input drive ring. E) Input ring for the 100kW magnetic gearbox and the F) topologically optimized sand printed mold for the input ring.

1.2.2.3 Cost Evaluation

Cost evaluations were conducted based on 1) the FDM strategy from Phase 1 which involved a sparce-fill polymer impression mold and 2) the cost of 3D printed sand part body outlines that did not include the gates, risers, printer rigging, etc… Here we are comparing the costs related to the supplanting conventional impressions. The cost associated with the FDM method includes materials cost (ULTEM) based on part volume. The cost associated with the 3D printed sand method include mold print volume and print time.

In practicality, there are additional costs incurred over the estimated values in Table 2 for both FDM and 3D printed sand. For FDM, once an impression is printed (cost in table + printer rigging flat rate ($5600) the print will be used to fabricate a sand mold. This involves a non-trivial effort on the part of the foundry, as casting models need to be employed to incorporate addition features (gates, risers, etc..) into the mold for effective casting and the sand mold themselves then need to be fabricated from the impression. For 3D printed sand, the part body accounts for approximately 60% of the total sand volume for the print (estimated cost value presented in Table 2). This partial model was elected to effectively compare apples to apples with the FDM method cost estimation. The additional costs related to 3D printed sand involves printer rigging, the increased final sand print volume, the foundry casting model design of the gate, riser, and chiller systems. The additional costs for each method were assumed to be comparable, but realistically the FDM method is likely to incur greater additional costs to produce the final sand mold.

The three housing components (Table 1) were evaluated for FDM printing and while feasible and less costly than conventional methods, the size and complexity of the parts would require a budget outside the scope of the current project. Further investigation is necessary to determine the feasibility of 3D printing sand molds for casting the housings.

Table 2. Cost estimations of print materials for FDM impression and 3D printed sand part body outline.

Part Type	Part Name	Approx. 3D Printed Sand Mold	Approx. 3D Printed FDM Pattern
Input Drive Flange	SH001	$2,656	$11,854
Input Drive Ring 2	SH002	$2,012	$9,202
Input Drive Ring 1	SH003	$2,279	$10,281
Rotor Drive Flange	SH010*	$4,040	~$15,000
Rotor	SH020	$4,111	$8,484

*This part was modified and renamed SH016A, though it does not affect the estimated cost.

Based on the cost evaluation, 3D printed sand was selected for the prototyping effort. Up to 3 sand molds could be printed before it would make financial sense to switch to an FDM impression. For context, if we desired 5 or more of each component then FDM would be the clear choice, but with the limited number of parts needed (1 of each component), 3D printed sand is the sensible option. With that said, both methods are far more cost effective than conventional prototyping methods.

When casting a one-off complex part, there is often some trial and error on the foundry floor. A first pour will indicate what casting parameters need to be altered to accomplish a complete fill of the mold, so a second (or even a third) mold may be necessary to pour a successful part on a seminal run. Based on the recommendation of our industry partner, David Weiss of Eck Industries, two molds of each of the five components were 3D printed from sand. The quotes values for mold modeling/cast simulation, 3D printing, mold assembly, casting, and final machining are presented in Table 1A in Appendix A.

1.2.3 Component Fabrication – Mold Assembly, Casting, and Machining

3D printed sand molds were commissioned through Eck Industries from an external printing house. An ExOne 3D printer was employed. Figure 5 shows the assembly of pieces of the 3D printed sand mold for part SH020. Figures 5B, 5C and 5D show the core box being built into the mold assembly. The core box is a vital component of the sand mold as it creates the internal void left in the eventual aluminum component. The bluish-white film seen in some of the images is a solid-state lubricant that acts as a mold release for easy removal of the cast part. Figure 5F shows industry partner, David Weiss (6' 3"), standing next to the 3D printed sand mold after the pouring of molten aluminum. A highly castable Al-7Si-2Ce alloy was selected based on the casting models and part size. After pouring, the components were heat treated to a T7 condition and all parts were dye penetrant inspected for cracks and shrinkage. All parts past inspection and met specifications outlined by Emrgy prior to the necessary machining operations.

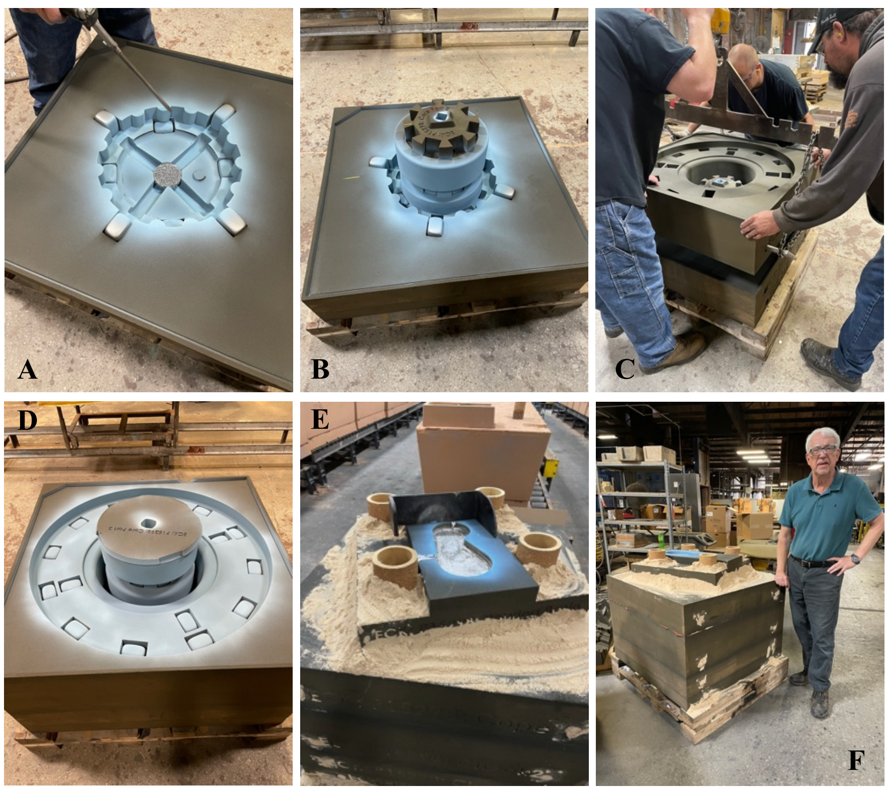

Figure 5. A-D) A series of photographs displaying the 3D printed sand mold assembly process prior to pouring molten aluminum. E,F) Assembled sand mold after pouring molten aluminum.

Figure 6 displays photographs of the cast component at various stages of finishing. Initially, when the part is removed from the sand mold (Figure 6A) there are regions of the casting that are excess due to the additional features needed for effective casting described previously. These additional features are removed (Figure 6C) by rough cutting operations, e.g. band sawing. This results in a casting weight and a final part weight (Table 3). The part was then sent to a machine shop to get the important technical features of the casting to the tight tolerances required for the application outlined by Emrgy (Figure 6D). A non-trivial factor in generating these prototype components involves acquiring quotes for machining these large custom parts. An exhaustive search for quotes yielded mixed results ranging from 'no-quotes' where a machine shop is unwilling to quote due to uncertainty or inability to handle such a large part, to exceedingly high cost for one-off part machining. Ultimately, General Manufacturing provided quotes that fell within the project budget. The quoted cost for machining can be found in the Appendix A.

Figure 6. Photographs of casting, part SH020. Component A) immediately after removal from sand mold, B) after sand blasting, C) after removal of additional mold features, and D) the finished part a machining.

Table 3. The casting weight after the pour and the final component weight after final machining.

Part Type	Part Name	Casting Weight (lbs)	Component Weight (lbs)
Input Drive Flange	SH001	320	160
Input Drive Ring 2	SH002	140	67
Input Drive Ring 1	SH003	258	80
Rotor Drive Flange	SH016A	996	515
Rotor	SH020	383	315

SH016A (Figure 7) was the most difficult part to cast from a technical standpoint. Because of the large size and complex aspect ratios, this part required an extensive casting modeling effort from Eck Industries and resulted in the largest casting weight (996 lbs) due to the additional features needed for a complete fill of the mold. On average, the parts required 3 iterations of solidification modeling to fully develop the gating system which was able to produce substantially defect free castings. For the part simulation pictured in Figure 7B, the run time of the model was 40 hours on an eight-core parallel processing machine with an additional 8 hours to set up the model. The run time roughly scales to total part volume, so run time was less on the smaller parts. In Figure 7, there is a large flat cylinder of solid aluminum that was a necessary additional feature to facilitate effective casting. This cylinder will be removed during machining (though still pictured in Figure 7A). The final part weight was 515 lbs. Figure 8 shows the part SH001 on a machining fixture (Figure 8A), and after all finishing operations (Figure 8B).

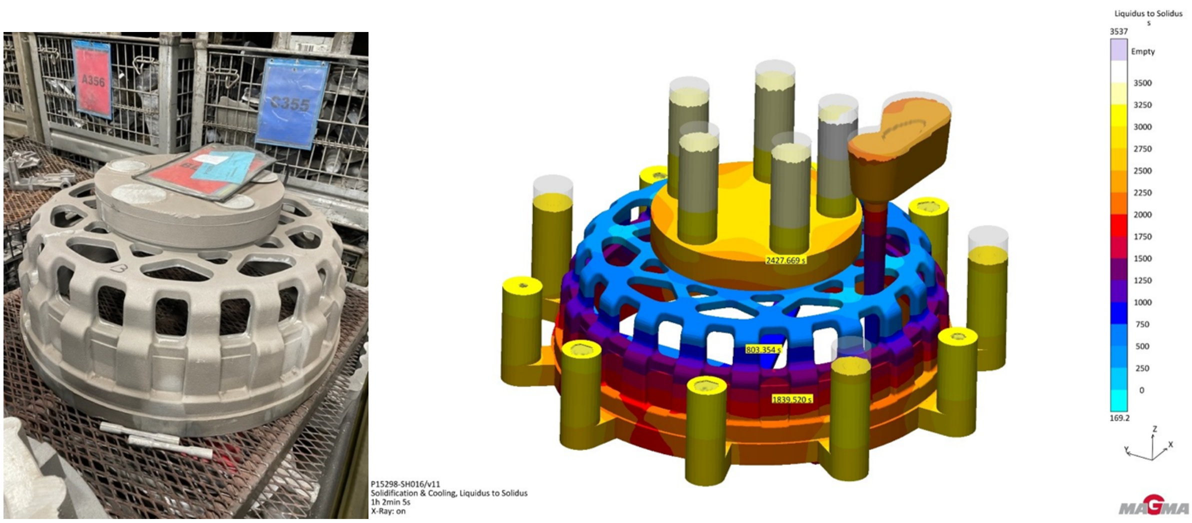

Figure 7. A) Component SH016A after rough cutting and before final machining, and B) an example of the casting simulation output.

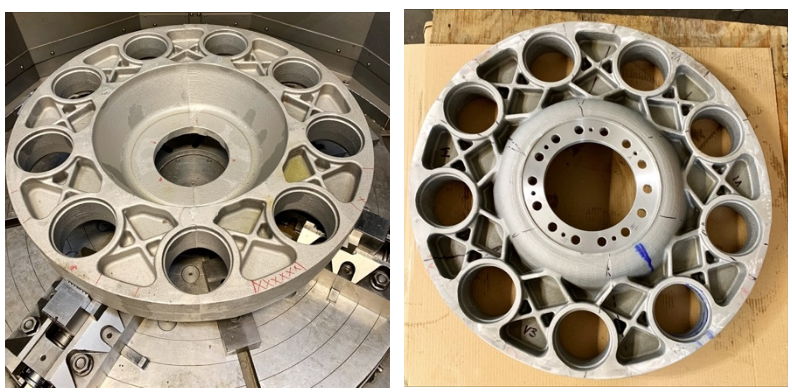

Figure 8. Component SH001 A) placed on a machining fixture and B) the opposite side of the finished component.

All parts were successfully cast to the specifications outlined by our industrial partner, Emrgy, though they were not without issue. Some of the casted features on part SH002, while reaching the target specification, were too thin to hold with the machining fixture in order to achieve the required tolerances. This was not a deficiency in the casting procedure and execution, but in the initial part design. Often when casting a part that requires a post-casting machining process, extra material is intentionally designed into the casting to avoid this very issue. These issues can be foreseen and avoided in many cases, though when prototype parts are being cast for the first time, the part designer and casting mold designer will not always be aware where a machinist will be required to fixture a part. In this particular case, the feature that was lacking material for fixturing needed an extra 1/8” of stock, as recommended by David Weiss of Eck Industries and confirmed by our machine shop vendor, General Manufacturing. This particular complication reinforces the need for flexible prototyping options such as 3D printed sand molds. Should comparable issues arise during conventional subtractive process for producing impression molds, significant sunk costs would result. Furthermore, upon completion of the broader magnetic gearbox effort, Emrgy has begun redesigning particular components, including, stators and rotors, promoting the impact of using cost saving when producing a one-off part.

1.3 IMPACT

Prototyping is a high-risk endeavor for industry and is often prohibitively expensive. AM approaches for prototyping and manufacturing have the potential to significantly minimize costs for industry by reducing prototyping duration, labor, and material waste. While AM methods have inherent higher material costs and limitations on scalability, the reduction in labor costs and elimination of significant subtractive efforts more than compensate for these drawbacks in the two cases explored during Phases 1 and 2 of this work. For the case of FDM, as demonstrated in Phase 1 and confirmed in the current effort's cost estimations, FDM is a viable and, likely, a preferred option for both prototyping and low- to medium-level manufacturing over the conventional sand cast methods. Issues relating to scalability are not of concern as the impression mold for a given part is analogous to the conventional impression mold and yield comparable numbers of sand molds to produce parts. Furthermore, FDM printed impressions can be produced cheaper and more rapidly than conventional wood, polymer, or metal impressions. In fact, the significant decrease in cost can enable a company to produce more impression molds for a given part allowing for increased sand mold production in parallel and, thus, faster production of cast parts overall. The findings of this study show that for early, proof-of-concept stage prototyping, where further design modifications are anticipated, 3D printed sand molds are the most affordable and fastest route to large, complex component castings. This holds true when less than 3 castings of a single geometry are needed. Here we demonstrate reduced AM machine time by only printing the mold wall thickness that is necessary, analogous to a sparce-fill approach employed in Phase 1. This work addressed the need for shorter design cycles in modern manufacturing and reduced overall prototyping costs. Employing these AM approaches can reduce the expected 5-year design cycle down to as low as 1 year from concept to functioning component, while reducing cost significantly. Smaller companies, such as our partner, Emrgy, will use these strategies to enable complex prototyping where previously it has been cost prohibitive.

Emrgy's impact statement: *"As a small company innovating a new technology, Emrgy has a great need for fast, economical prototyping and flexible tooling. Our technology relies on cast components to achieve significant and unique geometry at low volumes, but historically our conventional sand castings have required 6+ months of lead time to create and validate the tooling at a great expense. The manufacturing of Emrgy's cast components has created significant hurdles that have slowed the development process and hindered our ability to advance the TRL of our design. Using additive manufacturing for tooling could enable Emrgy to rapidly test or deploy components at a lower cost than conventional molds. We have learned that using additive manufacturing may also reduce the machining time required to finish these castings, thus reducing the unit's total cost. This is especially valuable for a company with a young technology, where we are constantly learning new lessons that require us to modify the cast geometry after only a few parts have been produced. Relying on conventional molds has been expensive and inefficient as Emrgy's technology continuously evolves. In the prototyping phase, 3D printed sand molds provide a path for Emrgy to rapidly prototype and test to deliver the best design faster and with a lower investment. In developing the manufacturing process, 3D-printed impression molds facilitate a shorter lead time to modify our tooling while the castings are being refined. From the point of view of the supply chain, these developments are a path to the commercialization of this product. The results of this program validate a lucrative manufacturing alternative for Emrgy to develop and scale our technology more efficiently than previously possible."*

References

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APPENDIX A. Cost Breakdown

Table 1A. Quote cost breakdown for molds/castings and for machining.

Part Name	Mold & Casting ($)	Machining ($)
SH001	12,926	9,900
SH002	13,807	13,500
SH003	15,530	13,500
SH016	22,030	16,200
SH020	16,635	18,250