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BIG AREA ADDITIVE MANUFACTURING APPLICATION IN WIND TURBINE MOLDS

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Abstract

Tooling is a primary target for current additive manufacturing (AM), or 3D printing, technology because of its rapid prototyping capabilities. Molds of many sizes and shapes have been produced for a variety of industries. However, large tooling remained out of reach until the development of large-scale composite AM manufacturing processes like the Big Area Additive Manufacturing (BAAM) system. The Department of Energy's Oak Ridge National Laboratory (ORNL) worked with TPI Composites to use the BAAM system to fabricate a wind turbine blade mold. The fabricated wind turbine blade mold was produced in 16 additively manufactured sections, was 13 meters long, had heating channels integrated into the design, and was mounted into a steel frame post fabrication. This research effort serves as a case study to examine the technological impacts of AM on wind turbine blade tooling and evaluate the efficacy of this approach in utility scale wind turbine manufacturing.

Introduction

The purpose of this paper is to identify potential use of Additive Manufacturing (AM) in the production of composite parts for wind energy systems.

AM, more commonly referred to as 3D printing, is a fast-growing industry in which recent technological advances have expanded its use beyond rapid prototyping. AM encompasses techniques applicable across multiple material types—most commonly polymers, metals, composites, and ceramics—that use computer-rendered designs to produce a near-net-shape part, layer by layer. Current costs for both polymer-based and metal-based AM systems keep AM out of large-volume production, but advancements in AM techniques will lower per-unit costs and advance designs beyond the capabilities of current conventionally manufactured (CM) components.

In the wind industry, current and research and development-level (R&D) AM technologies have potential for considerable impact on the prototyping and manufacturing cost of wind energy tooling and components. In the future, AM technologies could enable on-site manufacturing of turbine components as well as production of site-optimized components that are tailored to the unique wind and grid resources of a given location. For example, lower-cost and faster production of blade molds can increase the rate at which industry prototypes and conducts full-scale field testing of novel designs. Easier prototyping opportunities could be extended to customized nacelle designs and turbine configurations. AM could be used to create specialized tooling for the manufacturing of conventional components. AM will also allow for the development of components designed to better suit the specifications of their use, including lower materials requirements.

Insights gained from this project can be applied to the manufacture of other components for wind energy systems. Additional analysis of AM's current and newly-designed wind system components, the use of alternative materials, and on-site manufacturing potential is recommended. Rapid development of polymer and metal AM capabilities continue to cause costs to decline, which makes finding break-even points of AM and CM parts a constant moving target. Future R&D and analysis will further identify cost reduction opportunities and limits to AM applications.

Big Area Additive Manufacturing

Conventional fused deposition modeling is based on melting and extruding a filament of thermoplastic feedstock. Prior work shows that the peak flow rate is limited by the rate at which the filament can be melted [1]. For larger print volumes (at least 15 times the build volume of desktop-size consumer-level AM systems), technologies are developing. For example, Cincinnati Incorporated partnered with ORNL to developed the Big Area Additive Manufacturing (BAAM) process in 2014, which scales the extrusion process from desktop-sized AM systems of 1-5 cubic inches per hour to over 1000 cubic inches per hour [2]. To achieve high print rates, material pellets are used, which also significantly lowers the material cost (from \$110 – \$220/lb to \$3 – \$5 / lb), in combination with an optimized feed screw that reduces throttling of the pellet flow into the material. BAAM is an extrusion process that uses injection molding material for the feedstock and a single screw extruder for melting and metering the flow rate (see Figure 1) [3]. A gantry system, commercialized by Cincinnati Incorporated (see Figure 2), moves the extruder in x, y, and z directions to build the part. The extruder is capable of delivering 100 lbs/hour of thermoplastic materials from pellet feedstock. The gantry system is capable of achieving 200 inch/sec peak velocities with 64.4 in/s^2 accelerations and position accuracy in the 0.002". The use of carbon fiber reinforcement in the thermoplastic resins increases the part strength and stiffness [4]. Just as important, carbon fiber reinforcement also increases thermal conductivity and reduces the coefficient of thermal expansion lessening the need for a heated chamber to produce large parts (see Figure 3 and Figure 4) [5]. The elimination of the oven significantly decreases the energy intensity, which is the manufacturing energy required per kilogram of product. As shown in Figure 5, conventional FDM systems with heated chambers have a 100 kW-hr/kg energy intensity. Desktop systems that have similar production rates have a 5.5 kW-hr/kg energy intensity suggesting that the oven accounts for 95% of the energy consumption in FDM production. BAAM further reduces the energy intensity to 1.1 kW-hr/kg by significantly increasing productivity from 1 ci/hr to 2500 ci/hr, and BAAM parts are manufactured at room temperature. Due to its higher build rates and build sizes, BAAM's initial targeted applications is in the tooling industry. Specifically, in large, complex injection molds that are needed to produce CM polymeric and metal parts at a low cost.

Figure 1: BAAM Extruder

Figure 2: Cincinnati BAAM

Figure 3: Section of wind turbine mold

Figure 4: Printed prototype house

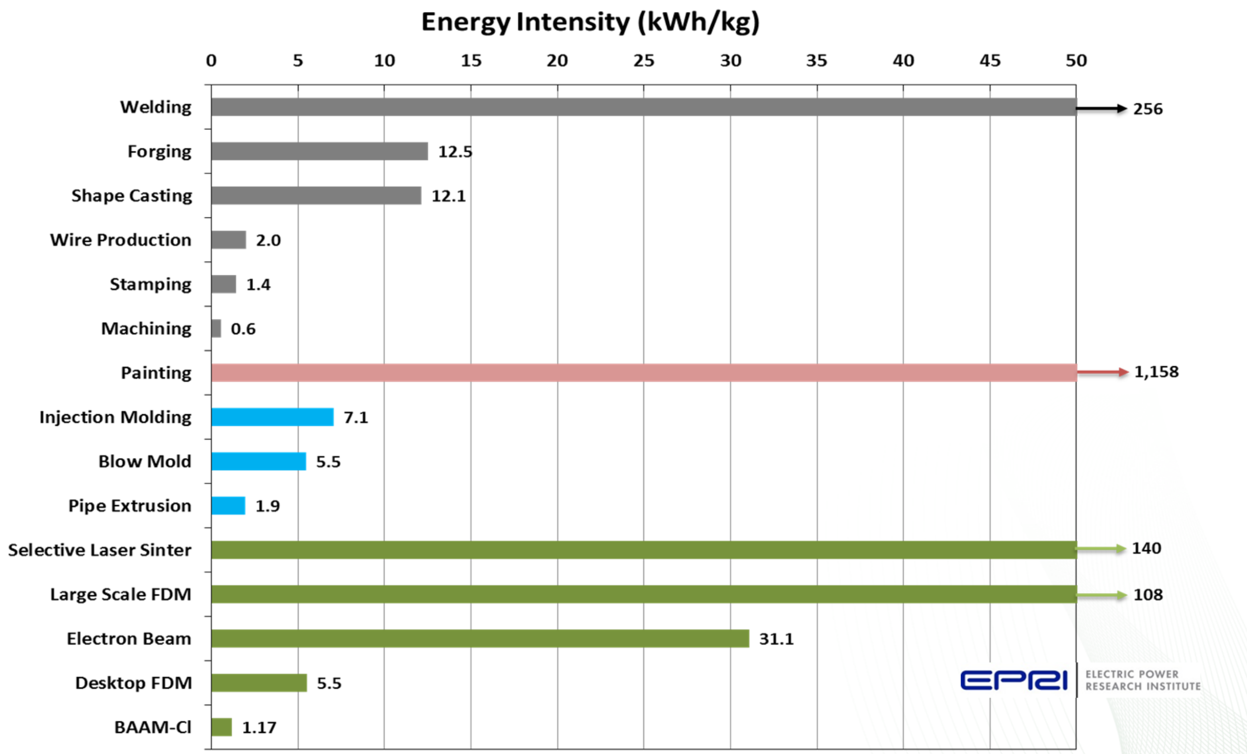

Figure 5: Energy intensity for manufacturing

Therefore, the combination of lower energy intensity, higher productivity, and lower material cost suggests that there will be a significant production cost reduction with BAAM when compared to conventional AM systems.

Applications of Current Additive Manufacturing Systems in Wind Power Systems: Fabricating Blade Molds

AM is hindered by limited production rates, expensive materials, processing costs, and small build volumes. These conditions serve to significantly limit the applicability of AM to wind energy system production. Commercial turbines are large systems where individual components often exceed 50 meters in length. The sheer size and mass of these components combined with throughput requirements largely preclude the application of current AM technology in wind power manufacturing.

However, several application areas have been identified where economic and technological incentives make AM processes viable for current production. Furthermore, if wind applications were used as a target to drive the development of AM systems, more applications with significant economic benefits become achievable.

The first identified wind application for AM, and the target of this study, is in the manufacture of molds for wind turbine blades. As described previously, tooling is a primary target for the current state of AM technology given the less stringent requirements for material performance and certification. AM molds of various sizes and shapes have been produced for a variety of industries. Large tooling, however, remained out of reach until the development of large scale composite AM processes like the BAAM-CI. Figure 6 shows the ORNL/TPI AM blade mold demonstrator produced as a collaboration between ORNL and TPI and funded by DOE's Advanced Manufacturing and Wind and Waterpower Offices.

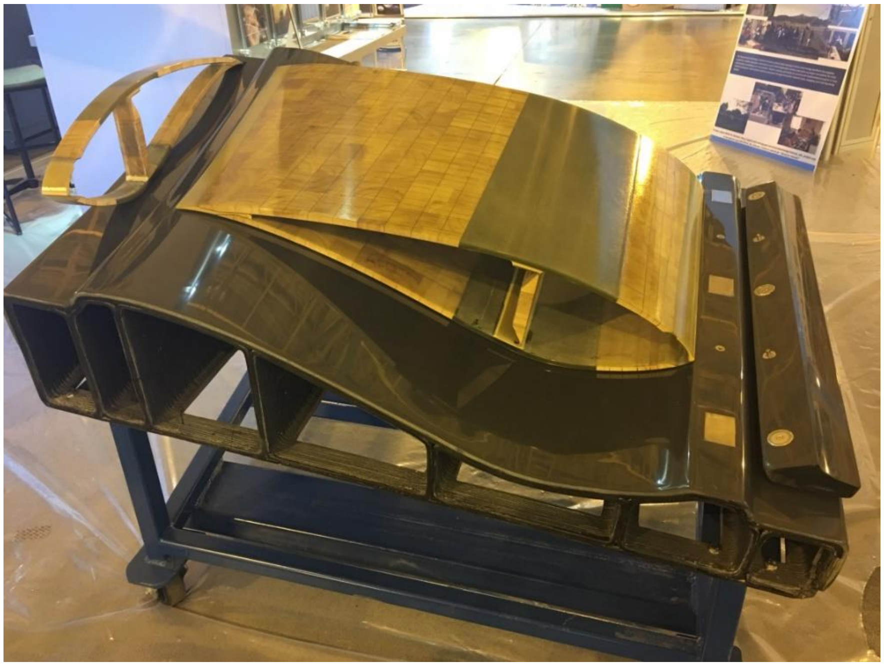

Figure 6: Additively manufactured blade mold and produced blade section.

The traditional blade mold manufacturing process is a multi-step, expensive operation. First, a plug is manufactured by subtractive machining of foam and tooling resin. This multi-piece assembly takes several weeks to months to produce from CAD drawings that are then used to generate CNC toolpaths. From there, the plug is shipped to the mold manufacturer where it is qualified and aligned. The mold manufacturer then applies a release agent and lays up fiberglass of sufficient thickness to support the molding operations. Miles of heating wire is manually embedded in the underside of the mold and arranged in zones of similar area. Then a steel frame is manually erected and attached to the mold prior to removal from the plug. From one plug set, up to eight molds can be produced amortizing the cost. For the production of one prototype mold, or a small set of molds, this cost can be prohibitively expensive, often reaching millions of dollars.

ORNL- TPI Scaled Wind Farm Technology (SWiFT) Facility Mold

To study the effect of wakes in large wind farms, the Sandia SWiFT facility uses a scaled wind farm. These turbines require custom blades to simulate the dynamics of their larger counterparts. The blades are scheduled to be produced using additively manufactured molds produced in partnership between ORNL and TPI and funded by the Department of Energy's (DOE) Advanced Manufacturing (AMO) and Wind and Water Power Office (WWPO). This research effort serves as a case study to examine not only the technological impacts of AM on wind blade production, but also the economics of AM at the large scale using BAAM technology.

Mold Requirements and Risk Reduction Exercise

The first step to the project was to define the mold requirements. For the resin infusion, there were a number of critical performance targets for the mold necessary to successfully manufacture blades. These targets included operating temperature, temperature gradients across the surface of the molds during service, mold distortion, vacuum, and life. The team identified three goals for each metric. The first was the target necessary for the success of the project. The second was a stretch goal that, if passed, would qualify the process for low volume production. Finally, the ultimate goal for the technology was to meet the targets necessary for full scale production. The metrics and goals for the project are outlined in Table 2.

Table 2: Project Metrics and Goals

Parameter	Target (this project)	Stretch (low volume)	Production
Substrate bond interface and coatings	Short beam shear test with no failure of interface at ambient	Short beam shear test with no failure of interface at 40 C	Short beam shear test with no failure of interface at 70 C
Mold temp (+/-5 C)	Ambient (need oven)	40 C (resin flows)	70 C (fast cure) with 100 C peak
Mold distortion	Match HP to LP at ambient less than 1% of chord	Match HP to LP at 40 C less than 1% of chord	Match HP to LP at 70 C less than 1% of chord
Vacuum drop	30 mbar over 30 minutes	15 mbar over 60 minutes	15 mbar over 60 minutes
Assembly of mold pieces	Meet gap tolerance (defined next page) at Room temp	Meet gap tolerance at 40 C	Meet gap tolerance at 70 C
Life	4 blades	12 blades	1000 (production)

The first phase of the project focused on risk reductions steps. The team designed a series of experiments to ensure that the BAAM molds would achieve the targets. High risk items included the heating (achieving the target temperatures and temperature gradients), distortion, and vacuum integrity. In terms of vacuum integrity, the team elected to coat the printed mold with fiberglass. The mold was designed 4 mm under the target mold lines. TPI coated the molds with 8 mm of fiberglass that was then machined to the final surface geometry and finish. The second item was the heating of the mold. It was determined that additive manufacturing could enable a very novel approach to heating. Rather than manually inserting miles of conductive heating wires, the molds could be designed with ducting directly printed into the structure. Small heating elements and blowers could be easily and rapidly installed in the molds, taking the time for installation of heaters from weeks and even months to a single day.

Table 2: Performance Metrics and Goals

Figure 7: Integrated ORNL/TPI heater units in blade mold section

Figure demonstrates the arrangement of heater units in the SWiFT mold set for the uniform heating of the mold surface. Each channel has been designed to be of equal surface area to reduce non-uniformity of the temperature profile over the surface of the mold. Hot air is circulated through the mold until the surface temperature reaches the desired set point; then the set point is lowered to a maintenance level.

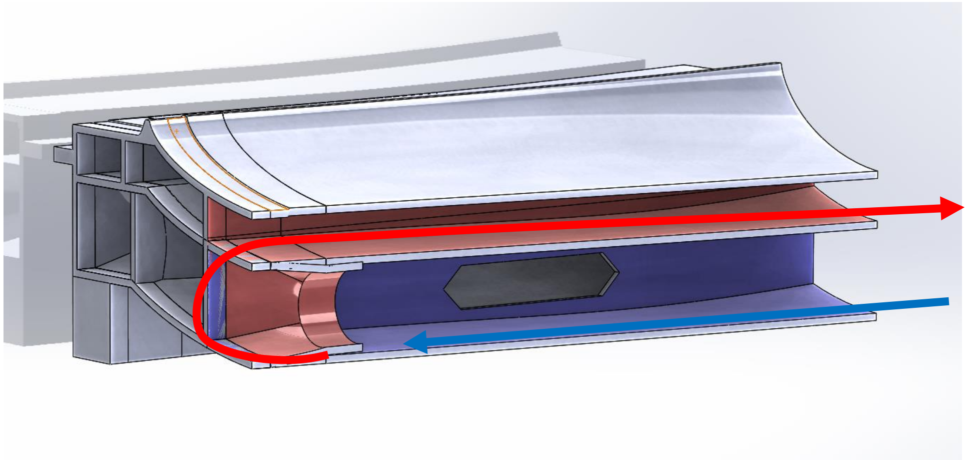

Figure 8: Airflow in mold section

A cross sectional view of the second mold section is shown in Figure 8. Arrows illustrates the heat flow, in that hot air exits the heater unit and flows along the surface of the mold where it loses energy and recirculates forming a closed loop. The functional structure of the AM component is used not only to achieve the desired surface geometry, but also to provide a housing for the heating unit and to distribute the heat uniformly throughout the structure. AM, in this example, enables functional structure and eliminates the manual labor associated with the emplacement of the heating system. Furthermore, a failed heating unit is easily replaceable via a pocket on the underside of the return channel.

A single section was manufactured and evaluated for performance (see Figure 9). A series of experiments were conducted to evaluate the performance (distortion, temperature gradient, vacuum integrity) of the mold. A laser tracker (see Figure 10) profiled the accuracy of the mold at room temperature. The heaters were turned on and the system was then brought up to the target temperature. At target temperature, the laser scanner measured the hot surface profile, and thermal imaging cameras measured the temperature gradients across the surface (see Figure 11, Figure 12, and Figure 13). The temperature gradient was measured at +/- 3C at 40C exceeding the requirements for the stretch goal. As shown in Figure 14, surface variations are under +/-0.025", approximately 0.1% of the chord. In terms of vacuum, the system exceeded the target of 15 mbar over 60 minutes. Therefore, the risk reduction exercise demonstrated that the AM mold sections exceeded the stretch goal requirements.

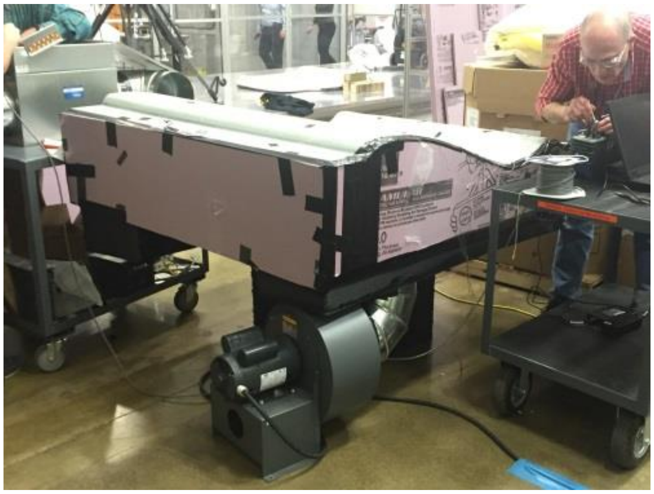

Figure 9: Test section

Figure 10: Laser tracker

Figure 11: Thermal imaging camera

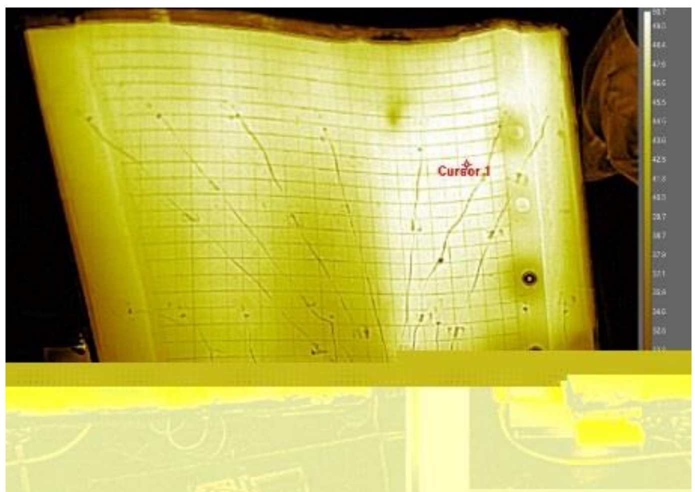

Figure 12: Output of thermal imaging camera and thermocouples

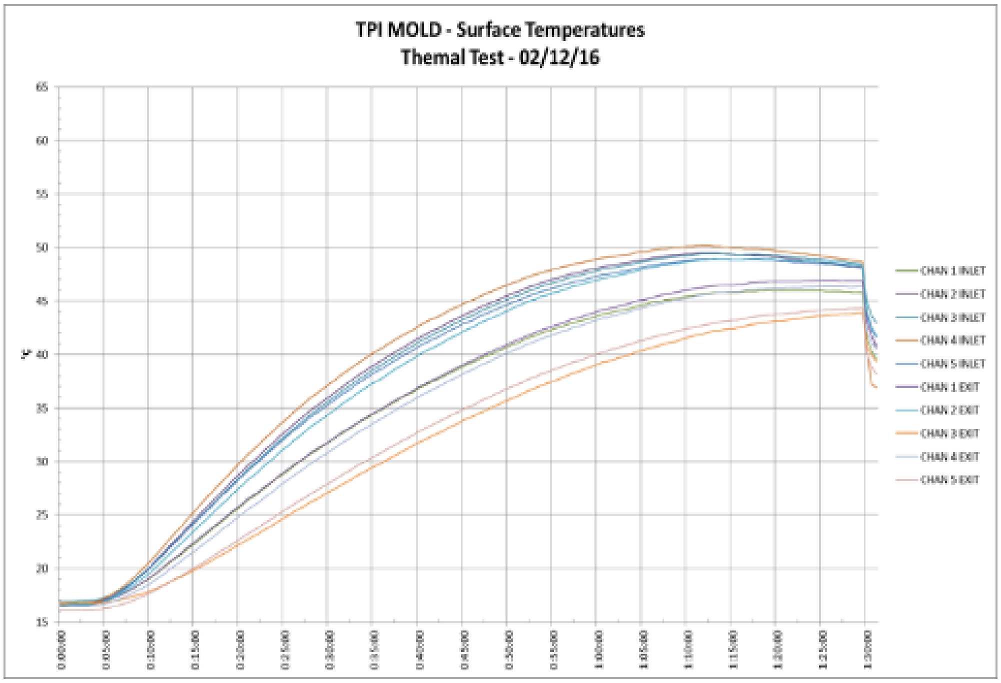

Figure 13: Thermocouple output

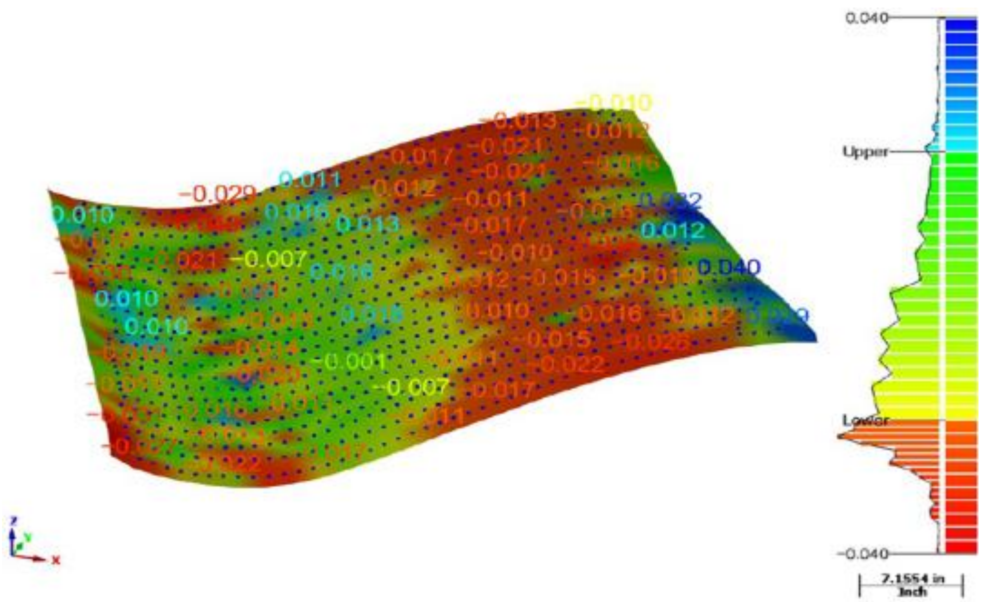

Figure 14: Measured surface variation at molding temperature

Printed Mold Manufacturing

After successfully achieving the goals through the risk reduction exercise, the project transitioned to the development of a full scale 13 m blade mold. From a manufacturing perspective, the mold proved to be better suited for vertical printing (see Figure 15). The work volume in the BAAM system was 8 ft wide, 20 ft long, and 6 ft in height. Therefore, each mold was made from eight segments (see Figure 16) , printed one at a time except for the smaller tip sections which were printed in twos.

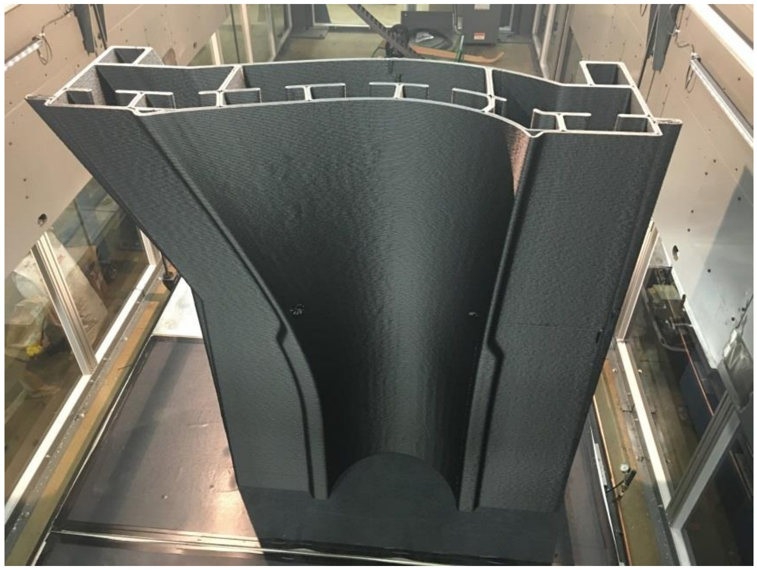

Figure 15: Printed low pressure side section 1 in the BAAM CI printer

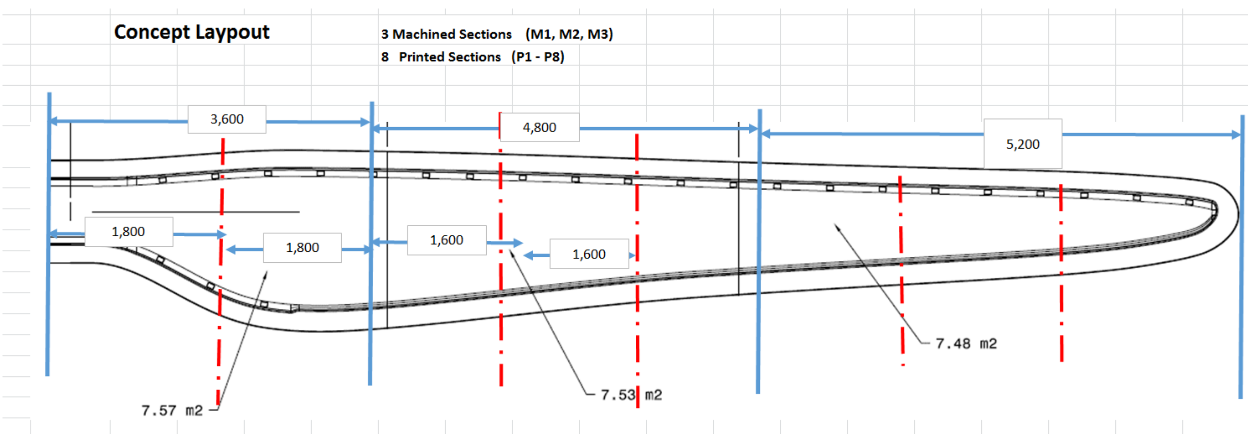

Figure 16: Mold sections

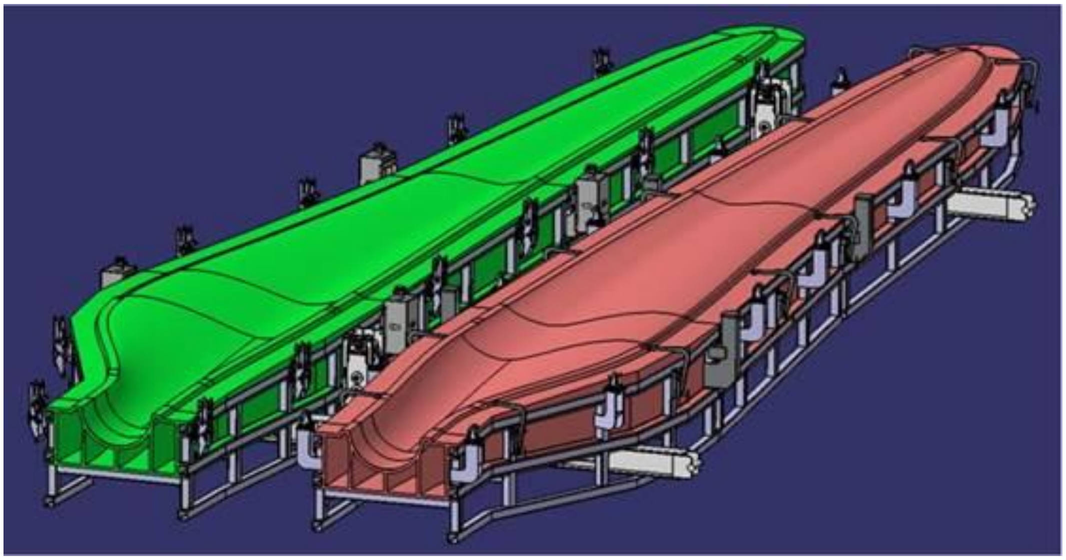

Figure 17: ORNL/TPI AM blade mold conceptual model

Each section is printed on end to maximize the resolution of the BAAM process and reduce the required support material as shown in Figure 15. Figure 18 shows the sections of the SWiFT AM blade mold printed prior to covering it with fiberglass. While many of the technical opportunities of AM in wind mold production are addressed in the production of the SWiFT mold, it also serves as a tool for the evaluation of economic incentives for similar molds on larger scales.

Figure 18: 5 of the 8 low pressure side SWiFT mold sections

After completion of printing, the molds were coated with fiberglass (see Figure 19) and machined to the final target surface (see Figure 20). The molds were fitted to be inserted into the egg crate structure (Figure 21) and were finally polished for operation (Figure 22). As of the writing of thispaper, one full set of blades has been manufactured (see Figure 23, three in total) with no discernable wear on the molds.

Figure 19: Fiberglass surfaced printed component

Figure 20: Section being machined

Figure 21: Assembly in egg crate

Figure 22: Final molds (high pressure and low pressure)

Figure 23: Finished blade

Conclusions and Future Applications

AM is finding more and more industrial applications in the area of molds, jigs, and fixtures. The automotive, aerospace, and appliance industries are rapidly transitioning to printed tools because of the complexity, high cost, and long lead times associated with these parts.

In terms of scale, there are new equipment manufacturers developing systems that are one to two orders of magnitude larger and faster than the current abilities of the Cincinnati BAAM. Ingersoll Machine Tool company announced the partnership with ORNL to develop the Wide High Additive Manufacturing (WHAM) system, see Figure 24 and Figure 25. The system will have a build volume that is approximately 25 feet wide, 20 feet tall, and 100 feet long and is scalable to much larger dimension. The production rate will start at 1000 lb/hr but is scalable to higher rates. This scale system enables the direct manufacture of parts (molds, blades, nacelles, etc.) that are competitive with current wind manufacturing needs.

Figure 24: Front view WHAM

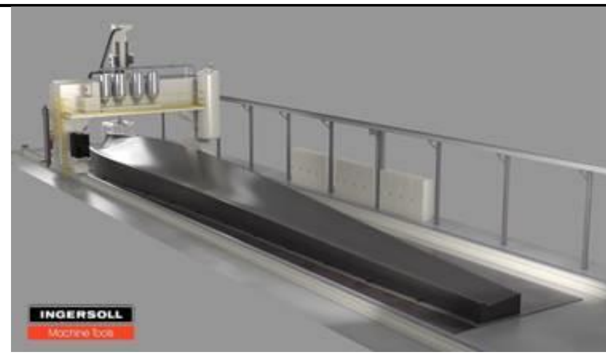

Figure 25: Rear view WHAM

Given significant leaps in material properties and out of plane printing, there is potential to directly manufacture wind turbine blades (see Figure 27). First, from the materials perspective, everything used to date in the BAAM process is based on short chopped carbon fiber. These materials are ideal for tooling because of their high stiffness, but they do not have the strength needed for strength limited structural applications. There will be a need for long or continuous fiber reinforcement to directly manufacture wind turbine blades. In addition, to keep part weight down, it will be necessary to print core structures (such as foam) to achieve specific strength and stiffness requirements. Systems such as the WHAM will have the ability to print, machine, and coat all within one machining center. At rates of 1000 lb/hr and greater, it is feasible to envision rapid automated manufacturing of customized wind turbine blades with multi-material (carbon fiber, glass fiber, foam, etc.) solutions.

Figure 26: 3D printed wind turbine blade

Acknowledgements

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