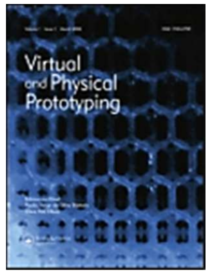

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Using Big Area Additive Manufacturing to directly manufacture a boat hull mould

Big Area Additive Manufacturing (BAAM) is a large-scale, 3D printing technology developed by Oak Ridge National Laboratory's Manufacturing Demonstration Facility and Cincinnati, Inc. The ability to quickly and cost-effectively manufacture unique moulds and tools is currently one of the most significant applications of BAAM. This work details the application of a BAAM system to fabricate a 10.36m (34ft) catamaran boat hull mould. The goal of this project was to explore the feasibility of using BAAM to directly manufacture a mould without the need for thick coatings. The mould was printed in 12 individual sections over a five-day period. After printing, the critical surfaces of the mould were CNC-machined, the sections were assembled, and a final hull was manufactured using the mould. The success of this project illustrates the time and cost savings of BAAM in the fabrication of large moulds.

Keywords: large-scale additive manufacturing; 3D printing; boat hull mould; tooling; Big Area Additive Manufacturing; BAAM

Introduction

Oak Ridge National Laboratory (ORNL) and Alliance MG, LLC wanted to explore the feasibility of using Big Area Additive Manufacturing (BAAM) to directly manufacture a boat mould with minimal post-processing in the form of thick, expensive surface coatings. In previous work (Nuttall 2016, Post 2017), ORNL created room temperature vacuumed assisted resin transfer (VARTM) moulds for wind turbine blades and small canoes. The tooling produced for the wind turbine project required extensive and expensive post-processing to achieve the desired surface finish. The coatings were a major cost constraint that detracted from the savings in time and surface finish. The other major constraint in previous work was the necessity of a large, steel framework to ensure the stability of the mould. The following project was a technical collaboration exploring the feasibility of producing a boat mould with minimal post-processing and no supportive framework to address the drawbacks from prior moulds to address the manufacturing needs of the marine industry.

Background

Traditional boat manufacturing requires a mould to manufacture the hull. Making this mould is a two-step process that starts with a plug, which is a positive form of the finished part that is used to produce the negative mould. The plug production begins by building a frame made of soft or hardwood and foam, clay, balsa, or c-flex. Typically, a base skeleton is made up of wood to support the plug. Then depending on the method, the skeleton is filled in with balsa, wooden planks, clay, foam, or c-flex to resemble the form. The form is then wrapped with fiberglass cloth or fibre-reinforced polymer and then coated with resin multiple times. The surface is then sandable, and any indentations or voids are filled in with resin putty. Any protrusions on the form are sanded down. Then the entire form is sanded and polished until it is in tolerance and deemed ready to receive a hard, gel coating. After the gel coating is applied and has cured, the plug is ready to be coated in a release agent. After the release agent is applied, the plug is ready to be used to make the mould (Doane 2010, Allmand n.d., Fiberglass n.d., Coackley 1991).

Making the mould from the plug is a similar process where the plug is coated with release wax, a gel coat, and resin-wetted fiberglass laminates (Frederiksen 2013). It is left to cure, and then it is pulled from the plug. After polishing, the mould is now ready to produce boat components, and the plug is typically stored to make more moulds as the moulds deteriorate from use.

Large-scale additive manufacturing can eliminate the plug making process by going directly from the computer-aided design (CAD) model to the mould, which avoids the use of a plug entirely. Producing a catamaran boat hull mould using BAAM can enable faster design cycles and reduce costs in labour and materials. However, fundamental limitations of AM must be considered in the design of these tools to produce a mould with limited post-processing and no external supporting structure.

Designing and Printing the Mould

The boat mould produced and detailed in this work is 10.36m (34ft) in length and is the shape of a single hull of a catamaran. Two finished fiberglass parts are made from the single mould to form the complete hull of a catamaran vessel. Alliance MG, LLC provided the model of the completed vessel from which surface data for the catamaran mould lines were extracted.

From the surface data, flanges for bagging were added, and a frame was designed to support the structural loading during the moulding and demoulding operations. Stock was added to the mould surface for subtractive post-machining to achieve the desired surface finish. The BAAM printer's volume is 2.44m (8ft) by 6.01m (20ft) by 1.83m (6ft), which is not large enough to print the mould as a single piece. To produce a 10.36m (34ft) print, the design was split into six sections, each approximately 1.83m (6ft) long. In order to machine the bow and stern sections, the head of a 5-axis CNC router must be able to fit into the mould and achieve the desired orientation. Therefore, to alleviate the machining issues, each section of the six sections was split into two parts: one for port and the other for starboard resulting in 12 printed parts for the complete mould.

These prints were designed and completed in a vertical orientation to eliminate the need for support material and to ensure the mould surface was built in the highest resolution plane (Figure 1a and b). Figure 1c shows the projected toolpaths if the mould was printed in the horizontal position. This orientation was considered a poor choice because the top is heavily stair-stepped and would have required an extreme amount support material, e.g. many times more than the print itself. It would also have resulted in more voids and porosity in the moulding surface and longer layer times, decreasing the interlaminar strength.

[Place Figure 1 here.]

The mould was printed with 20% chopped carbon fibre reinforced acrylonitrile butadiene styrene (CFABS), which reduces the coefficient of thermal expansion and reduces the amount of distortion and warping in the final part. Therefore, the major contributor for overall surface accuracy is caused by the geometry of the bead, or extruded material, and not thermal distortion. To reduce the impact ridges, which are a result of the 3D printing process, have on the mould surface, each part was overbuilt by 0.38cm (0.15in) on each critical mould surface. This excess material was meant to be machined away to produce the desired surface finish. Ideally, the depth of cut leaves the machined surface at the centre of the bead where it is likely to have the least number of defects and voids. The BAAM system printed the mould sections at a travel speed of 27.51cm/sec (10.83in/sec) at a flow rate of about 35.38kg/hr (78lb/hr). As shown in Figure 2, up to three sections of the mould were printed at once, and each section took approximately 12 hours to print, resulting in a total print time of approximately 48 hours. In total, the mould required 2,494.76kg (5,500lb) of material that costs approximately $11.02/kg ($5/lb), making the cost of materials $27,500.

[Place Figure 2 here.]

Boat Mould: Machining and Assembly

Each section of the boat mould had to be machined to get the desired surface finish. Once each section was fabricated on the BAAM system, they were left to cool in the build volume while still attached table to reduce warping. Then each section was transferred to a Thermwood 5-axis CNC router. To ensure accuracy, the router was calibrated to each section using a Faro laser tracker. Using a SMR tracking ball to take data and form a point cloud, the machined surface of each part was best fit to its position in space. This data was used to align the design file to the part on the router table and match the part's coordinate system to the reference frame of the router. The tooling chosen was a 1.27cm (0.5in) ball end mill with a 0.127cm (0.050in) step over path to achieve the desire surface finish. The machining process and final machined section are shown in Figure 3. Each section was machined independently, and interfacial features were machined into the ends of the parts.

[Place Figure 3 here.]

Once all the mould sections were post-processed, it was time to assemble them. Assembly occurred in three stages. First, the starboard and port sections were glued together to make up the six sections of the mould. Two technicians used three threaded rods to align the starboard and port sections. Each section was elevated on inflated innertubes to allow the mating features to align the parts. Once aligned, an epoxy was applied to the seams that cured in 60 minutes, and the rods were tightened (Figure 4a). The hour cure time was necessary to allow for alignment adjustments. To ensure each section matched up as designed, wooden support beams were inserted at the top of the mould to control the span. Then, a tensioning strap wrapped the two sections together and applied pressure (Figure 4b and c). This process was repeated six times and each section took approximately three hours before they were left to cure for 24 hours.

In the second stage of assembly, the sections were assembled from the stern to the bow matching the contours carefully as each new section was added (Figure 4c).

Finally, to remove the requirement of a load bearing structural frame, the sections were post-tensioned by steel rods. To help distribute the load, aluminium bulkheads were manufactured and joined to the end sections of the mould. These served as foundations for long tensioning rods to bear the load across the entire mould. The long tensioning rods had threaded ends for springs, washers, and nuts to provide controlled tensioning. The design load on the rods was sufficient not only to eliminate the possibility of delamination of the layer to layer interfaces, but also to make the mould completely self-supporting.

Once the entire mould was assembled and tensioned, another 24 hours of cure time were required before the tensioning straps were removed. During the cure time, a pair of steel beams with lifting eyes and casters were attached below the mould in preparation for moving the mould. Attaching both casters and lifting eyes allowed for better methods to transport the large mould. The final mould (Figure 4d) was scanned with a Faro 3D Scanner and compared to the original CAD model. The fit had an average deviation of less than 0.127cm (0.050in) for the complete mould surface.

[Place Figure 4 here.]

Moulding Process

This project investigated using resin infusion with the additively manufactured mold. Resin infusion uses the surface of the mold directly as the molded surface. To do so, the mold must be vacuum tight and exhibit what would be considered a “Class-A” surface finish. To achieve these requirements, the mold was transported to a finishing facility where the surface was smoothed. Air pressure tools and abrasives were used to finish the surface to 180 grit and ultimately to a 320-grit surface finish. The surface was then treated with a commercially available thin vinyl ester mould coating.

To test if the mould was ready to produce parts, it was covered with a vacuum bag and placed under a vacuum. The test required that the mould hold a vacuum for an extended period without losing vacuum. The mould passed the test and was ready to attempt test part production. The test part was infused and comprised of composite fabrics and foam cores over a section of the full boat hull. First, the surface was coated with a release agent and then the cores and fabrics were applied to the surface. A vacuum bag was then placed over the test section and sealing tape was used to seal the bag directly to the surface. Once sealed, air was evacuated using a vacuum pump, and a stable vacuum was established. A resin system introduced the resin to the bag and was pulled through the foam cores and composite fabrics. The resulting part was uniformly integrated under atmospheric pressure. After infusion, a resting period was necessary to allow the part to cure in the mold before it was pulled.

The test piece was successful, and a subsequent full test of the mould was executed as seen in Figure 5. The entire mould surface was prepared for the thin, vinyl ester coating (5a); the full surface was then coated (5b); the mould was infused with resin using the VARTM process (5c); and once cured, the final hull was removed from the mould (5d). The mould was inspected for damage after the full test, and two problem areas were identified. The two areas developed "pneumatic cracks" and showed evidence of air leaks. The cracks themselves were not obviously visible and were the result of poor application of the coating onto the additively manufactured mould. However, the cracks were not detrimental to the mould and were fixed by applying additional coating to the problem areas.

[Place Figure 5 here.]

Conclusion

The goal of this project was to explore the use of printed materials for mould manufacturing without the need for expensive coatings or a steel substructure. A mould was produced with a thin, commercially-available vinyl ester and was able to meet the desired surface finish requirements. The project also demonstrated the feasibility of producing large moulds divided into sections without a subframe by utilizing a post-tensioning system to reduce the cost of materials for the mould; The post-tensioning technique improves the flexibility and increases the potential modularity of these types of moulds.

Currently under study is the maintenance and repairability of the mould as it is being used. This work is continuing through the efforts of Alliance MG, LLC. Limitations to this technology include the necessity of machining and sealing the mould after printing and 3D printed materials' thermal limitations, generally. The thermal limitations are only relevant if the moulding processes has exothermic reactions that could degrade the mould. If exothermic conditions are of concern, more expensive materials can be used to fabricate the mould, but this limits the cost saving potential of this process.

Acknowledgements

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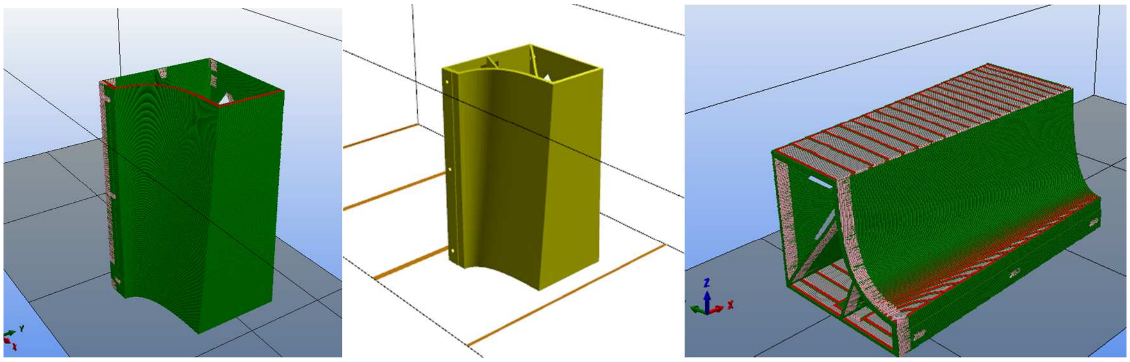

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a *b*

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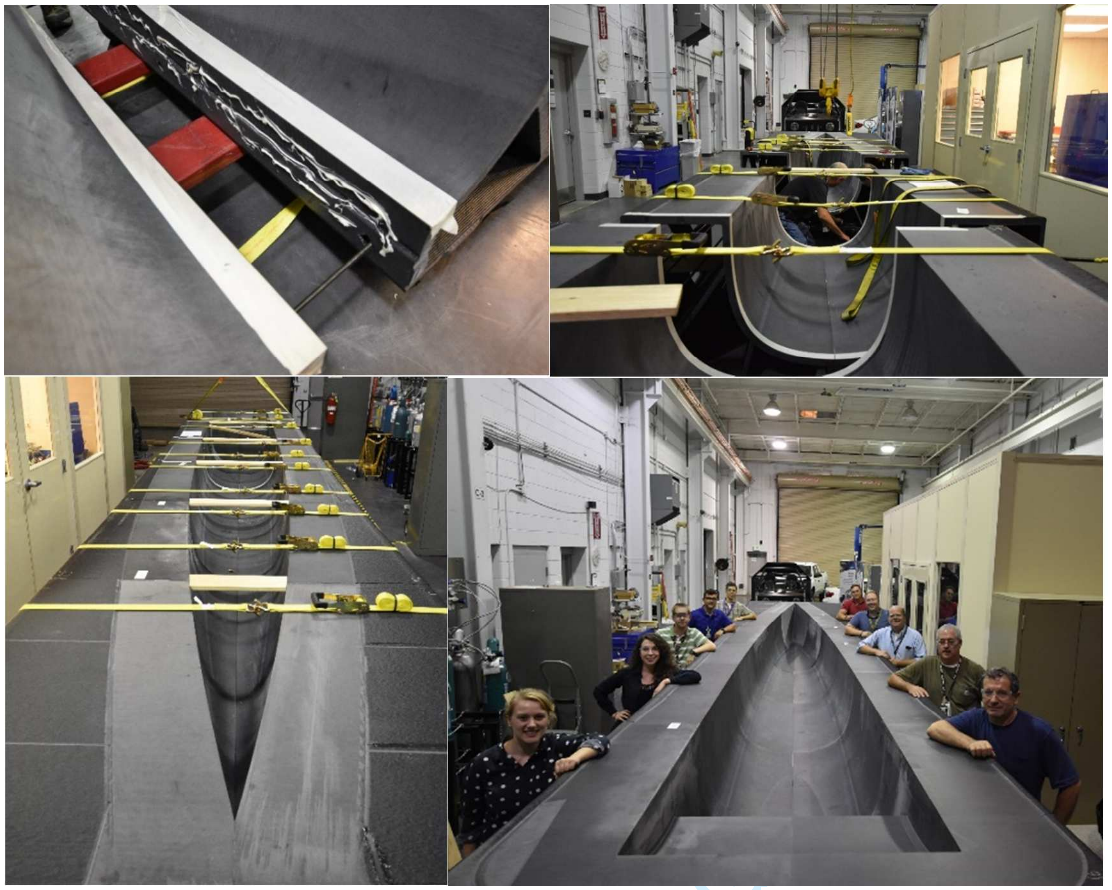

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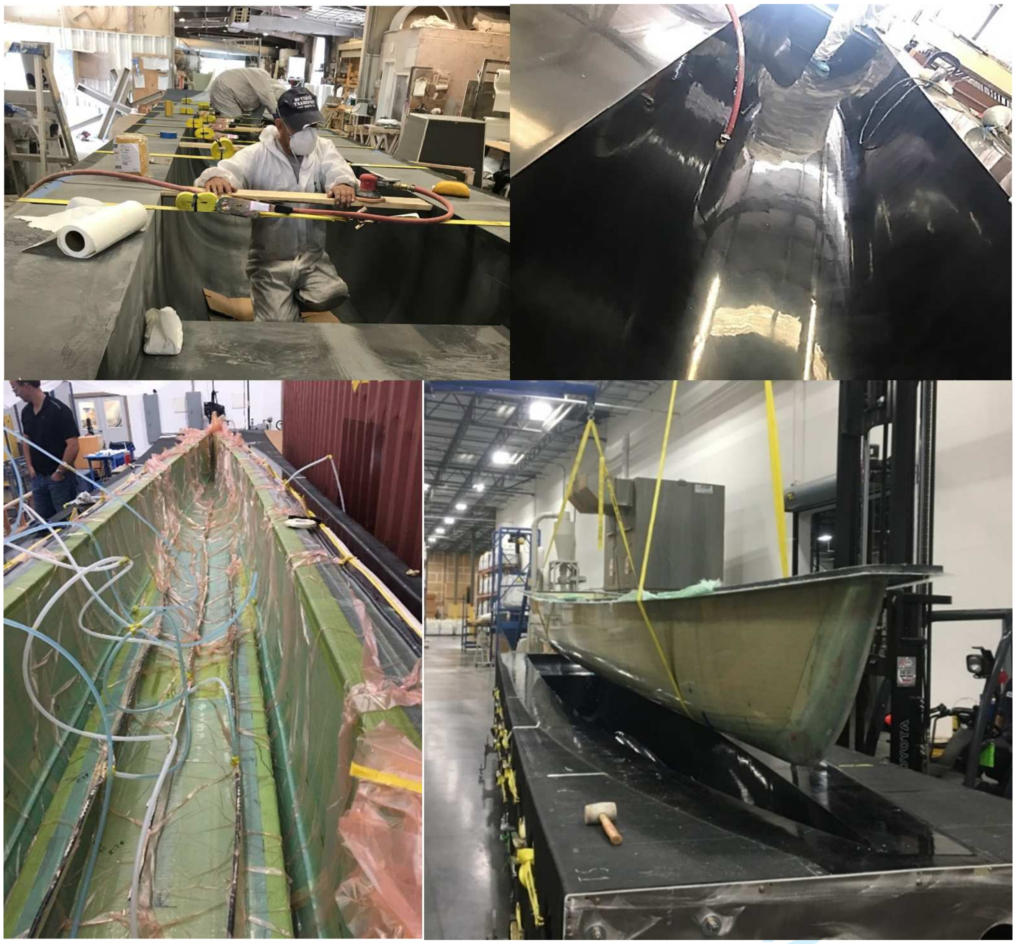

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