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Recent Innovations in Additive Manufacturing for Marine Vessels

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Abstract

The terms Additive Manufacturing (AM) and 3D printing describe several very different methods for producing 3-dimensional forms. AM technologies present new opportunities for the yacht design and small boat manufacturing sectors, particularly the Fused Filament Fabrication (FFF) method. The design and construction of marine vessels present unique manufacturing challenges and opportunities for AM. While many AM methods are not well-suited for small boat manufacturing, some of these technologies are already being used by the marine industry. While AM technology is currently limited by the speed, scale, and material constraints of 3D printing materials and equipment, these technologies are being successfully scaled up for the marine industry by academic researchers and manufacturers. Additive Manufacturing technology will need to continue to advance in order to adapt itself to the complex material, structural, and mechanical requirements of the marine industry. The technical challenges that remain for large-scale AM to produce entire boats are the water-resistance of extruded materials, surface integrity (smoothness), the structural integrity of surface manifolds, and the integration of structural reinforcement systems.

1. Introduction

A brief overview of Additive Manufacturing technology

The terms Additive Manufacturing (AM) and 3D printing describe several very different methods for producing 3-dimensional forms. First developed in the 1980s for small scale rapid prototyping applications, AM remained a high-end prototyping tool and an area of research and development for nearly 20 years (Kantaros et al., 2021). This method for constructing 3-dimensional forms typically uses layers of deposited or hardened materials to build up an object in laminar procession. There are several distinct AM processes that fall into five main categories. 1) Photopolymer rapid prototyping using liquid resin bath process: the Digital Light Processing (DLP) method uses a high intensity light source to harden sequential layers of a form in a liquid resin bath; Stereolithography (STL) uses a similar process with ultraviolet lasers and a horizontal skimming tool for uniform application of each layer of resin. These techniques are typically used for high resolution prototyping. 2) Photo-activated or liquid chemical binder-activated granular material processes: Selective Laser Sintering (SLS) uses dry granular plastic materials that are superheated with a laser to adhere to one another in successive layers; Selective Laser Melting (SLM) and Electron Beam Melting (EBM) both deploy a similar process but use metallic powders melted with either a high-

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power laser or an electron beam in a vacuum chamber. These techniques are typically used for high-performance prototyping and one-off manufacturing for the automotive and aerospace industries. Binder Jet (BJ) printers typically use a liquid chemical binder sprayed onto successive layers of powdered material to build a 3-dimensional form; however, they can also be used with common materials, such as water and powdered clay or porcelain, and this method is often used for prototyping low-resolution and low-performance objects in design and form-finding applications. 3) Wax-casting process: this technique, also known as Material Jetting (MJ), uses hot wax extruded onto a surface to build three dimensional forms in laminar layers, sometimes deploying a second print head to build scaffolding supports from a different material; this process is typically deployed in the jewelry industry for lost wax-casting smaller objects. 4) Cut shape lamination method: Laminated Object Manufacturing (LOM) uses a series of shapes cut from a common material, such as paper or plastic sheets, which are glued or fused together using a heated roller to build up an object in a series of layers; this is an inexpensive and fast prototyping or modeling tool most often used for design and form-finding. 5) Thermoplastic deposition process: Fused Filament Fabrication (FFF), also known as Fused Deposition Modeling (FDM), feeds a filament of thermoplastic polymer through a heating element and extruder nozzle, depositing a rapidly cooling molten material onto a build surface in successive layers; this method has been successfully scaled up with wide-bead thermoplastic pellet extruders deployed on robotic arms and mounted on gantries. Additives such as chopped fibers, cellulose pulp, or continuous stranded fibers can be added to thermoplastic mixtures. FFF is an extremely common prototyping method that has exploded in popularity, with many unique applications, including in the nautical design and manufacturing industry (Jo & Song, 2021; Kantaros & Piromalis, 2021).

When Adrian Bowyer published his open-source RepRap Project in 2005 (Bowyer, 2014) 3D printing entered the mainstream with a “self-replicating” machine using the FFF method to reproduce 3-dimensional objects. The introduction of the first MakerBot in 2009 made off-the-shelf 3-dimensional printers affordable and easy to use for the general public (Goldberg, 2018). The commercial development of Large-Scale Additive Manufacturing (LSAM) in 2016 by the Thermwood Corporation introduced the possibility of building very large objects using a wide bead (3cm) extruder mounted on an industrial gantry, coupled with a CNC surfacing tool mounted on a second gantry (Scott, 2016; Wedgewood et al., 2020).

Other methods for AM are generally not particularly well-suited to scaling up for large product manufacturing for a variety of reasons: the inherent strength of certain materials (BJ and MJ), time-dependent chemical processes that may be optimized for thinner layers resulting in excessive build times (DLP, STL, SLS), the surface tension of liquid materials that can make large scale applications unfeasible (STL and MJ), and the requirements for the build chamber that may be sub-optimal for large-scale applications (for example, an unreasonably large vacuum chamber for EBM). FFF is the only method currently well-suited for potentially transitioning from large scale prototyping to large scale manufacturing applications, but additional challenges remain (Harris et al., 2017).

A secondary, but equally important, component of the AM process is the software that is used to drive 3D printers. All common FFF 3D printers resolve a form in a series of layers built up in a sequence. The orientation of the object relative to the extruder head and the platen or build surface can have a dramatic effect on the final object, including the amount of material used to produce the object, its material strength, and its structural performance. The proprietary slicer or CAM software tools that drive many 3D printers have pre-set values that make generic assumptions about how to produce 3D forms using a particular material or process. While they are convenient and easy to use, they mask important, and sometimes complex, aspects concerning performance that should be considered when producing an object. These aspects include the orientation of the object, the speed of material deposition, the density of the core material, and the configuration and location of support material.

Typically, slicer software used in FFF printers produce a form by tracing successive laminar profiles- driving the print head to a series of x and y coordinates to describe a horizontal “slice” and then activating the Z-axis servo motors once the layer is completed to begin the next horizontal slice. The most significant shortcomings of the laminar FFF printing method are 1) the inherent weakness of the bonds between the layers of deposited material (Kantaros & Karalekas, 2013; Doshi et al., 2021; Li et al., 2022; Zhang & Wang, 2020), and 2) the uneven or stepped surface characteristics of laminar extrusion of thermoplastic materials. Poor adhesion between layers can lead to sub-standard performance for objects built using this method (Kantaros et al., 2021; Rossi et al. 2016; Liu et al., 2022), and uneven surface characteristics may require labor intensive post-processing. Recent developments in non-planar FFF 3D printing point to one possible solution for this problem, simultaneously addressing the stepped appearance of tapered surfaces and the intralaminar weakness of objects manufactured using this method. The non-planar building method develops a form by dynamically activating the Z-axis servo motor along with the X and Y axes. The result is both a smoother appearance for inflected surfaces and potentially superior material performance for the built object (Alsharhan et al., 2017). This is an area of active research for nautical design applications for AM technology.

Initially introduced as a rapid prototyping tool for industrial and product design fields, AM is now used for a variety of direct to market manufacturing applications. Notably, these applications include the production of protective equipment in response to the COVID-19 emergency (Kantaros et al., 2021), as well as other health related products, including customized implants, prosthetics, orthodontic aligners, and other wearable medical devices (Dodziuk, 2016), as well as the production of pharmaceuticals (Nikitakos et al., 2021) and even replacement organs (Kantaros et al., 2016; Kantaros & Piromalis, 2021; Kantaros & Karalekas, 2014). Consumer product applications include a variety of objects and parts, including musical instruments (Kantaros & Diegel, 2018), toys, aerial drones (Galatas et al., 2018; Bishay et al., 2019; Negrelli, 2017), aerospace (Palomba et al., 2022), and automotive products (Savestano et al. 2016) Consumer electronics is another area of broad application for AM, as it includes both housing and customizable internal components such as circuit boards and microelectronics (Espera et al., 2019).

2. Materials and methods

Traditional technologies for building boats

Wood has been used for millennia to construct boats. Typically, wooden parts are joined together to create a singular hull form that contains a volume of space to pass through water. A surface above this volume of space protects it from water, sun, and weather, allowing passengers or cargo to travel with limited exposure to the exterior elements. The weakness of this construction method is the tendency for different parts of a wooden hull to move separately from one another. Wood also tends to shrink and swell with moisture content, and hulls are subject to deforming dynamic loads that can lead to wear between mated surfaces and gaps or voids in the components that make up the hull. Exposure to sun and the water also take their toll on the wooden components of a boat, as well as any metal or other material components that may be used to fasten them together. As tools for transporting people and materials, wooden boats are easily worn on interior surfaces due to the cargo and crew they transport and on their exterior surfaces due to lines, docks, and piers the hull may be fastened against. Finally, the marine ecosystem subjects the wooden parts of a boat to organisms that can degrade the integrity of the individual components. Frequent and regularly implemented maintenance is a necessary practice that has enabled wooden boats to remain solid and functional over time.

The 19th Century witnessed a complete transformation in the materials used to construct larger ships. While specialized metal components had been used in wooden vessels as fasteners for thousands of years and examples of military vessels that had been clad in metal sheets to protect their hulls from projectiles were quite common especially in the 18th and early 19th Century, the Industrial Revolution gave rise to steam powered ships built entirely from metal. While metal hulls presented a huge advantage in strength and durability, the design of these vessels still traced their conceptual roots to wooden boats and, therefore, suffered similar problems of wear, corrosion, and required maintenance. Metal frames replaced wooden ones, while steel plates fastened with rivets replaced wooden planks fastened with bronze nails-conceptually, the construction methods used to produce early metal ships was not far removed from how boats had been built for centuries (Allen, 1987).

The 20th Century witnessed unprecedented advances in metallurgic science and fastening technologies for ship construction. The application of steel welding to naval construction led to the first modern ship hulls since the invention of the dugout canoe that could be considered as singular manifold surfaces without any breaks in the continuity of their surfaces. The durability of metals and the new technologies for fastening ships together represented nearly ideal solutions for solving the problem of hulls made from multiple components and, therefore, for reducing periodic maintenance costs. However, these advances were only feasible for larger vessels; wood was still the primary material used for the manufacture of smaller vessels in the early 20th Century.

The 1950s saw widespread advancements in the development of industrial plastics, including composite materials. Experiments with glass Fiber Reinforce Plastics (FRP) led to the application of this material technology to the marine sector. This low-cost construction method fed growing market demand for smaller, inexpensive boats from a growing market- a post-war middle-class eager to enjoy recreational boating. FRP vessels can be produced with re-useable molds, an economical method for mass-producing low maintenance watertight hulls. The material properties of FRP allow for uniform, unbroken surfaces that avoid the typical problems of hulls made from multiple parts. FRP is now the most common material used for vessels below 40 meters, due to its material efficiency and the relatively low costs associated with its capacity for serial reproduction. Despite its widespread use, molded FRP has significant limitations for yacht manufacturing. Complex topological forms are often difficult to produce with FRP: they must be simplified to meet the draft angles for mold removal, or they must be broken into multiple parts and reassembled using handicraft processes. This reliance on imprecise hand craft can lead to significant errors and deviations from dimensional specifications. Due to labor costs and the precise dimensional and engineering requirements it is often not practical to produce certain marine components using traditional molded FRP manufacturing methods.

3. Examples and discussion

Additive Manufacturing in the contemporary yacht market

One of the greatest innovations for industrial design in the 21st Century is the development of Additive Manufacturing (AM). AM has taken off in the past decade with dramatic reductions in the cost of 3D printing materials and equipment. In response, industrial design is experiencing a significant change in the roles design development and prototyping play in the design process. To a limited degree, it is now possible to use AM for product manufacturing, especially when customization is a common product feature. There is enormous potential for this technology in the nautical design sector in the production of marine components and smaller vessels. In the past several years, there have been several examples of small boats that have been produced using AM technology. These first tentative steps in deploying a new technology for yacht manufacturing must be followed by additional advances in material applications, manufacturing processes and tooling design, and software tools for improving the speed, strength, and durability of objects made using this method (Nickels & Fowler, 2017). While the behavior of thermoplastic materials in a marine environment has been extensively studied, the effect of both mechanical and chemical aging on thermoplastic composite materials, and their tendency to absorb water depending on both temperature and mechanical stress, is of particular concern (Qin et al., 2020; Bel et al., 2021; Bardin, 2020).

The yacht design industry relies on molded FRP as the primary technology for producing small and medium sized yachts. This method uses expensive molds; formal variation and require simplification to achieve the necessary draft angles for removing objects from these molds are often constrained. Complex surfaces with undercuts or overhanging surfaces are difficult to produce, and customized forms are both labor intensive and expensive to manufacture. Furthermore, customized or hand crafted FRP components often suffer from dimensional variation and a general lack of control over the density, strength, and weight of hand-crafted parts. On the other hand, AM allows greater formal variation and topological complexity than traditional FRP. AM allows the designer to directly control the form, strength, and weight of a marine component. Objects made using AM demonstrate less deviation between their specified and actual dimensions, eliminating the need for expensive field measurement and complex templates that are typically required in the fitting out process.

The contemporary yacht market is currently geared toward semi-custom production: clients select vessels based on broad requirements such as size and cost, and customize the final product with various interior configurations, design finishes, and equipment packages. Modifications to the hull itself, while somewhat feasible, are often too expensive for the typical client. Typical hull or topside customizations that were simple modifications when most small boats were constructed using wood remain elusive, or prohibitively expensive, for those purchasing boats fabricated using molded FRP. Typical customizations, such as changing the interior ceiling height, the number or location of ports and hatches, or adding certain equipment such as a bowsprit or stern swim platform, prove very challenging for the contemporary yacht market to provide, given current manufacturing processes.

AM presents the opportunity for greater flexibility in the customization of yacht hulls at far lower cost, provided equipment can be scaled up and 3D printed material properties can rise to meet the exacting demands for the marine industry (Ziółkowski & Dyl, 2020). Despite current limitations in AM materials and equipment, several recent projects have shown great promise for future deployment of this technology at an industrial speed and scale.

3.1 Case study 1: University of Washington Fabbers Club Milk Carton Derby

Innovations: Materials, upscaling, low-cost tooling

In 2012, a student 3D printing club at the University of Washington used FFF AM to construct a small vessel for competition in a local regatta (Hickey, 2012) The race, known as the Milk Carton Derby, is a community fund-raising event to raise public awareness about pollution and recycling. The event is aimed toward informal floating vessel designs using repurposed containers- boatbuilding that might likely be taken on by local youth groups and volunteers more interested in recycling than naval architecture. Typical entrants to the race are not yacht designers and may have little to no knowledge about hydrodynamics or the development of stable hull shapes. The rules for qualifying in the event simply stipulate that all vessels must be made from recycled plastic milk jugs (**Figure 1**).

The students from the UW Fabbers team researched ways to process HDPE material from reclaimed milk jugs and developed a specialized extruder that they mounted on an industrial CNC plasma cutter. The material processing, testing, and development of this project demonstrates an innovative approach to working within challenging guidelines (HDPE is a notoriously difficult material to work with). The ad hoc bootstrapping approach to tooling development is admirable considering that the team developed the entire printing device without any precedent models. The UW Fabbers team printed a simple 2.13 meter (7 foot) vessel made entirely from containers that the students had collected. While the project is a primitive example of naval design, it demonstrates the ingenuity of an academic team working to solve the technical challenges of up-scaling materials with AM technology. This was the first full-scale boat ever produced using a large format 3D printer.

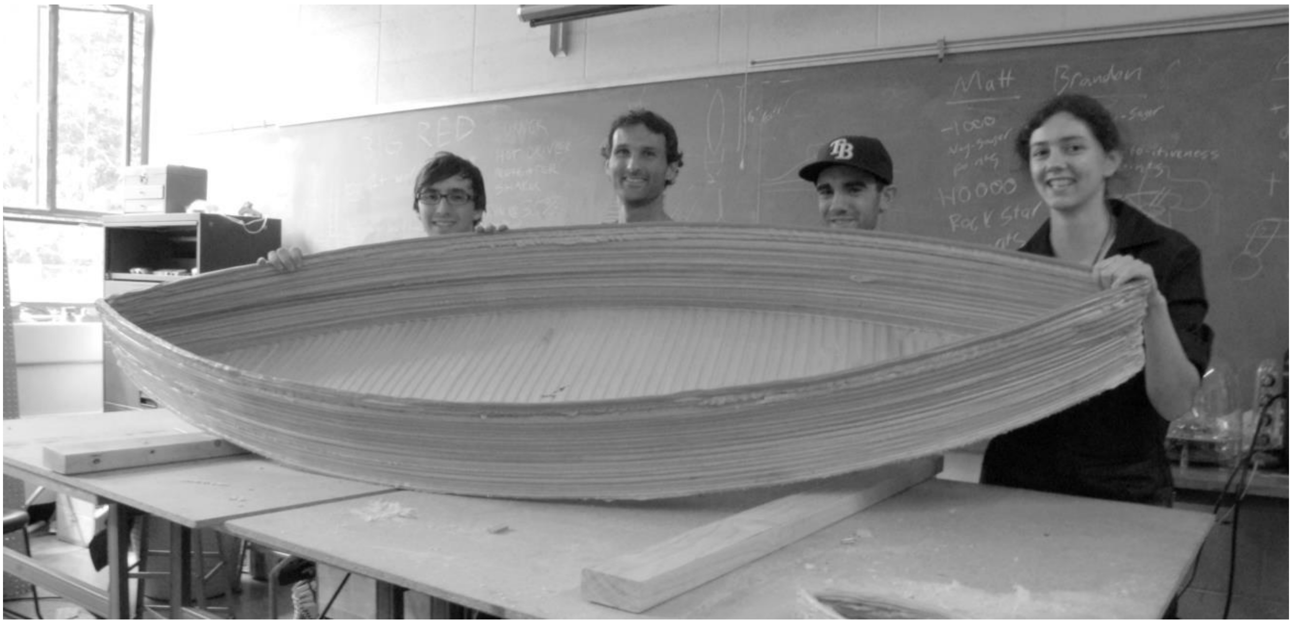

Figure 1 Image courtesy of University of Washington News (Hickey, 2012).

3.2 Case study 2: Oak Ridge National Laboratories Big Area Additive Manufacturing (BAAM) Demonstration Project

Innovations: Upscaling, multi-stage industrial tooling

In 2018, a team of researchers at the Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility in Tennessee was sponsored by the US Department of Energy Advanced Manufacturing Office to assess the feasibility of producing molds for the manufacture of FRP boat hulls using resource-efficient, fast, and cost-effective methods (Post et al., 2019). Over five days, the manufacturing research team used Big Area Additive Manufacturing (BAAM) to fabricate a 10.36 meter (34 feet) catamaran boat hull mold using a 2.44×6.01×1.83 meter (8×20×6 feet) gantry-mounted large format 3D printer. Typically, boat hull molds are built in a multistage process that is both labor intensive, reliant on traditional handicraft methods, and prone to formal deviations from the original intention of the naval architect or designer. BAAM has the potential to allow boat hulls to be produced directly from a computer-aided design (CAD) model. However, the surface characteristics of forms made from wide-bead thermoplastic extruders often require extensive post processing, using thick and expensive coatings, to both accommodate the uneven surface characteristics of extruded materials and to achieve the necessary smoothness required for boat hull molds. These molds also require additional support material and structures to prevent the mold from deflection due to loading and thermal stress in the manufacturing process. These inefficiencies and associated expenses may inhibit the widespread adoption of BAAM for the production of molds unless new design and manufacturing methods prove effective for mitigating these issues (**Figure 2**).

The research team at ORNL designed the catamaran hull mold to be produced in a four-step process of extrusion, precision milling, assembly, and surface finishing. The mold CAD model was designed with an integrated extruded structure, over-thickened walls to accommodate milling the finished surfaces, and assembly tabs for fastening the separate parts together. The mold was printed over 48 hours in twelve parts using 20 % chopped carbon fiber in an ABS thermoplastic. Each part was subsequently milled on a 5-axis CNC machine using a precision laser guided orientation system to align the physical coordinate system of the individual parts to the reference frame of the CNC machine. Finally, the milled parts were fastened together using threaded rods and glue before being sanded and finished with a thin coat of vinyl ester mold coating.

This demonstration project proved that an effective cavity mold can be produced with the requisite strength and surface qualities using a two-stage AM and surface milling method. Further, the team at ORNL showed that, with proper structural design and precision manufacturing tolerances, secondary structural elements and thick coatings need not significantly add to the cost of producing molds for boat hulls in the 10 meter size range. Finally, the mold was produced in only five days, demonstrating that the labor costs for producing a mold of this size can be significantly reduced using AM methods.

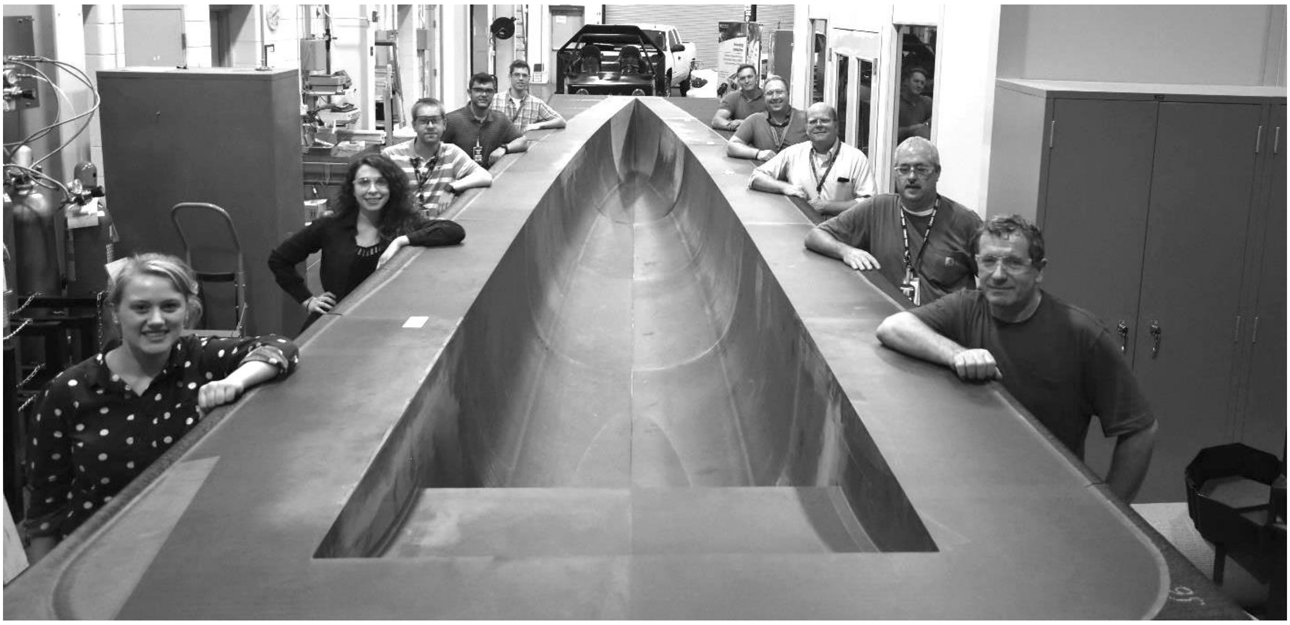

Figure 2 Image courtesy of Oak Ridge National Laboratory Manufacturing Demonstration Facility (Post, et al., 2019).

3.3 Case study 3: University of Maine Advanced Structures and Composites Center 3Dirigo Project

Innovations: Materials, Upscaling, Production Speed

In 2019, the University of Maine demonstrated the feasibility of using large-scale wide bead AM to produce a 7.6 meter (25 feet) deep vee-shaped boat hull in a single discrete object printing operation (UMaine News, 2019). This project produced not only the world's largest 3D printed object, but the first fully 3D printed boat hull. The boat was printed on a custom-built prototype Ingersoll Machine Tools plastic polymer printer capable of producing plastic polymer objects up to 30.5 meters (100 feet) long, 6.7 meters (22 feet) wide, and 3.05 meters (10 feet) high. It used a proprietary wide bead extruder head with a bio-based plastic polymer. The hull, weighing a reported 2268 kilograms (5000 pounds), was printed in under 72 hours (**Figure 3**).

This exciting achievement lends credence to the argument that it may soon be possible to use AM for producing small production boats and yachts. However, despite the very positive results of this fabrication experiment, there remain significant challenges for 3D printing entire boats. The hull produced by researchers at the Advanced Structures and Composites Center at the University of Maine weighs approximately 20% more than comparable vessels of the same general hull shape and size. It is currently undergoing extensive evaluation in an indoor testing facility featuring high-performance wind simulation in a multi-directional wave basin. Of particular interest is an evaluation of the ultimate water resistance of the hull to determine if it will form a truly watertight barrier that remains resistant to osmotic penetration over time. While we wait for the results of these tests to be published, it is apparent that boats produced using this method are not yet ready for the open market.

Figure 3 Image courtesy of University of Maine News (UMaine News, 2019).

3.4 Case study 4: Politecnico di Milano MOI Composites MAMBO Project

Innovations: Materials, continuous fiber, robotic arm, componentry

In 2020, the young Italian start-up firm MOI Composites launched MAMBO (Motor Additive Manufacturing BOat), the first Fiber Reinforced Plastic (FRP) motorboat fabricated using Continuous Fiber additive Manufacturing (CFM) technology (Politecnico di Milano, 2020). This project is part of a Politecnico di Milano spin-off program, supported by a team of sponsors and partners including Autodesk, Mercury Marine, and Owens Corning. This 6.4 meter (21 feet) fiberglass motorboat project, which debuted at the 2020 Genoa Boat Show, relied on a hybrid manufacturing process that included both AM using robotic arms and traditional handicraft FRP boat building techniques.

The hull was produced as 50 separate parts, extruded with a proprietary continuous resin impregnated glass fiber extruder mounted on a 6-axis robotic arm. The benefit of this method is the opportunity to orient fibers in multiple axes to substantially stiffen the surface manifold without significantly increasing weight. Typically, FRP hulls rely on a uniform wall thickness of resin impregnated glass fibers oriented in layers of uniform biaxial fabric optimized for areas of maximum stress. This results in heavier hull forms that do not efficiently manage weight using variable thickness and optimized fiber orientation. At a lean 800 kilograms (1765 pounds), MAMBO weighs over 30 % less than a production FRP hull of similar length. The separate hull components were bonded to a PVC core and laminated with several layers of glass fiber fabric before being integrated into the overall hull form. Finally, the exterior surface of the hull was sanded and faired before painting. While this project relies as much on traditional FRP handicraft techniques as advanced AM technology, it represents a first step toward directly producing FRP hulls from CAD files. Future applications of this manufacturing method will allow hulls to be produced using many fewer individual parts, representing a major reduction in labor costs. Most significantly, hulls produced using this method can be highly customized and optimized for various performance criteria with only modest variations in production costs (**Figure 4**).

Figure 4 Image courtesy of Politecnico di Milano (Politecnico di Milano, 2020).

3.5 Case study 5: Direct to Market Marine Components by Superfici S.c.r.l.

Innovations: Componentry, one-off manufacturing

Since 2016, the design laboratory Superfici S.c.r.l. based in La Spezia, Italy has accelerated the typical product development process for nautical design by designing and fabricating 3D printed one-off marine components (Loibner, 2021). The Sacs Marine 700 Series console is an award-winning demonstration project that uses computer modelling and AM to design and produce a direct to market product for the marine industry. The HSM plastic console was designed and fabricated in less than four weeks, with a small design and fabrication team including interns from the Design Navale e Nautico program at University of Genoa. The form of the console demonstrates, through its complex surface topology, that it cannot be fabricated using traditional FRP molded methods. It was designed using Superfici's proprietary componentry method and printed as multiple subcomponents using the FFF method on standard size, commercially available 3D printing devices (Nazzaro, 2019). The assembled form was coated with a thin layer of marine grade fairing material and finished with automotive paint. Strategic panels, wiring chases, and filler plates allow the console to be periodically updated with new electronic components without damage to the whole.

The innovation, demonstrated by Superfici S.c.r.l., lies primarily in the sophisticated use of componentry to create larger direct to market marine products that can be printed on standard off the shelf 3D printers. While it is unlikely that these design and fabrication methods will be deployed for mass production, it is an agile and adaptive approach for a marine market more likely to demand customized design solutions. The componentry approach demonstrated by this project lends itself to mass customization, and may be the best suited application, in the short term, for deploying AM in the marine industry (**Figure 5**).

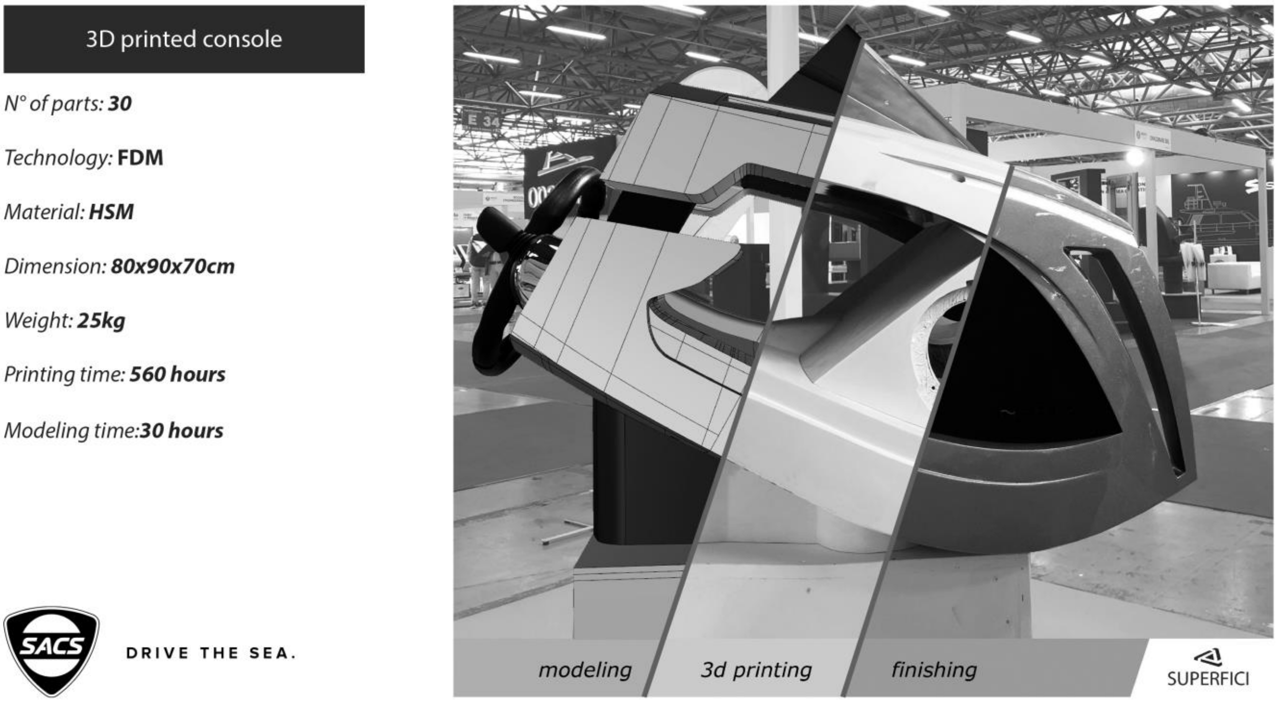

Figure 5 Image courtesy of Superfici S.c.r.l., (Superfici, n.d.).

4. Conclusions

The technical challenges that remain for large-scale AM to produce entire boats fall into four main categories. First, the material properties of various extruded thermoplastic composites that are subjected to the stresses and conditions of the marine environment over time must be studied more extensively to determine the effects of both mechanical and chemical aging on the materials themselves, as well as the assemblies that they comprise. Second, surface integrity: FFF methods rely on strong bonds between sequential laminar depositions of molten plastic materials. It is quite possible that using this method will prove exceedingly difficult to ensure a water-tight seal between layers, requiring all vessels to be coated with a secondary water-tight skin such as FRP, carbon fiber, or another material yet to be tested. This presents refitting challenges to extend the life of 3D printed yachts and challenges for recycling at the end of lifecycle. Third, laminar structural integrity: FFF methods typically use unidirectional laminar slicing for building up a manifold surface. Until such time that layers of material can be oriented in multiple directions to counteract forces in 3 dimensions, boat hulls will, of necessity, be required to be somewhat thicker and heavier, in order to resolve common loading conditions, particularly at points of inflection on their surfaces. Recent experiments with small-scale non-planar AM could prove to be very useful if applied to this particular large-scale 3D printing problem. Fourth, macro-level structural integrity: boat hulls are complex structural manifolds that must resist dynamic loads due to the force of the water pushing inward on the hull and the changing nature of loading conditions in the marine environment. Typical FRP hulls integrate structural elements made from metal or wood by chemically and/or mechanically bonding them to the hull manifold itself. These structural systems are optimized to reinforce the hull while also shaping spatial volumes to house equipment, cargo, and people. It is unclear if 3D printed materials will have the strength to replace these members or whether new structural integration methods will need to be developed. We can speculate about a robotic articulated arm 3D printing method that weaves a non-planar hull around a frame in order to integrate structural members, conduits, and other necessary systems into a monolithic hull. This process, however, will remain in the realm of fantasy until such time as manufacturing research catches up with our imagination.

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