ORNL/TM-2024/3329

Additive Manufacturing for Large Displacement Unmanned Underwater Vehicles (LDUUVs)

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March 2024

CRADA FINAL REPORT
NFE-19-07870

Approved for Public Release
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CRADA/NFE-19-07870

Manufacturing Science Division

ADVANCED PATHING SOLUTIONS FOR LARGE FORMAT POLYMER PRINTING

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March 2024

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UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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ACKNOWLEDGEMENTS

This project under CRADA NFE-19-07870 was conducted as a user project within the Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility (MDF) sponsored by the US Department of Energy Advanced Manufacturing Office (CPS Agreement Number 24761). Opportunities for user projects under the MDF Technical Collaboration Program are listed in the announcement "Manufacturing Demonstration Facility Technology Collaborations for US Manufacturers in Advanced Manufacturing and Materials Technologies" posted at http://web.ornl.gov/sci/manufacturing/docs/FBO-ORNL-MDF-2013-2.pdf. The goal of Technical Collaboration Program is to engage industry partners to participate in short-term, projects within the Manufacturing Demonstration Facility (MDF) to assess applicability and of new energy efficient manufacturing technologies. Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

ABSTRACT

Oak Ridge National Laboratory partnered with Anduril Industries to develop the process for adapting large format additive manufacturing for the production of underwater vehicles. This research started by defining and selecting a polymer for the vehicle panels. Coatings were tested at 9000PSI to ensure proper bonding to the 3D printed panels, then tensile tested to understand the mechanical properties. A vehicle panel fairing set was design optimized for the 3D printing process and then 3D printed. Additional work optimized coatings and tested additional reinforcements methods such as fiber weave and z-casting with fiber rods and resin. Finally, a full vehicle was constructed and successfully tested in open water by Anduril.

1. ADDITIVE MANUFACTURING FOR LARGE DISPLACEMENT UNMANNED UNDERWATER VEHICLES (LDUUVS)

This technical collaboration project (MDF-TC-2019-166) began on September 19, 2019, and concluded in December 2023. The collaboration partner Anduril Industries, formerly Dive Technologies, is a large business with over 2,000 employees. The results included characterization of materials for underwater vehicle applications and development of the necessary geometry and printing parameters to withstand water pressure and other loading scenarios encountered at depth.

1.1 BACKGROUND

Anduril Industries is currently in development of a UUV for use in commercial surveys as well as inspections of offshore wind farms and oil and gas fields. Anduril produces commercially available products with enough on-board energy and sensors to complete offshore survey at a much lower cost by decreasing the amount of topside vessel support required. Working with the DOE ORNL at the Manufacturing Demonstration Facility will enable collaboration on solving the challenges of manufacturing these underwater vehicles for offshore surveying. Specifically, manufacturing costs, biofouling, energy efficiencies, and robustness will be the primary focuses of this effort.

1.2 TECHNICAL RESULTS

1.2.1 Material and Coating Selection

The first decision was to determine a material for printing the underwater vehicle components. Based on material properties, including cost per pound, extrusion temperature, available fiber loading, and mechanical strength, ABS (acrylonitrile butadiene styrene) and PC (polycarbonate) were chosen. Both were loaded with 20% carbon fiber to increase stiffness and decrease thermal expansion. Print trials were conducted with both materials using a simulated geometry for the vehicle panels. To improve surface finish, the panels were printed with a very fine, 0.05”, layer height. This small layer height, combined with a wide bead width, 0.025”, created an aspect ratio that did not print well with polycarbonate. The resultant prints struggled with smearing and bulging, issues that were not present when using ABS.

With ABS selected as the initial printing material, research shifted toward coating selection. The goal was to determine a coating or preparation method that could easily be applied to the surface that would smooth the surface to reduce hydrodynamic drag and/or help improve the layer-to-layer bond, or Z-strength. Five options were selected, and 1 control without any modification was maintained (#1). Panel #2 used a TDSand coating which is a thermoset-based material designed for 3D printed components that can be sprayed. Panel #3 used XTC-3D, a resin-based coating for 3D prints that can be rolled or painted. Panel #4 was pressure tested, by Anduril, in water to 9000psi to remove porosity and entrained air from the polymer. Panel #5 was simply soaked in water. Lastly, panel #6 was coated with off the shelf epoxy and can be seen in Figure 1. Table 1 lists the six different panels and how the surface was prepared.

Figure 1: A 3D printed panel with epoxy coating.

Table 1: List of coatings for testing.

Panel #	**Coasting/Test**
1	Control Panel
2	TDSand Coating
3	XTC-3D Coating
4	Raw panel with 9000psi exposure/soak
5	Raw panel after ambient soak
6	Epoxy/HBP

1.2.2 Testing Coatings

To test the five coatings, hexagon shapes were printed with the CF-ABS material. The hexagons were cut at the corners to create individual panels of printed material. The coatings were then applied to the flat panels on just a single side. Once cured, at least one of each type of coated panel was sent to Anduril for underwater pressure testing. This testing was to simulate the high pressure experienced by the vehicle while under water. Some of the pressure tested panels were sent back to ORNL for the next step which was waterjet cutting the panels into dog bones to prepare samples in the X and Z direction. X represents the as-printed direction and the Z direction is orthogonal to the layers, intended to represent the most common failure mechanism for 3D printing. The results of testing the coatings can be seen in Figure 2.

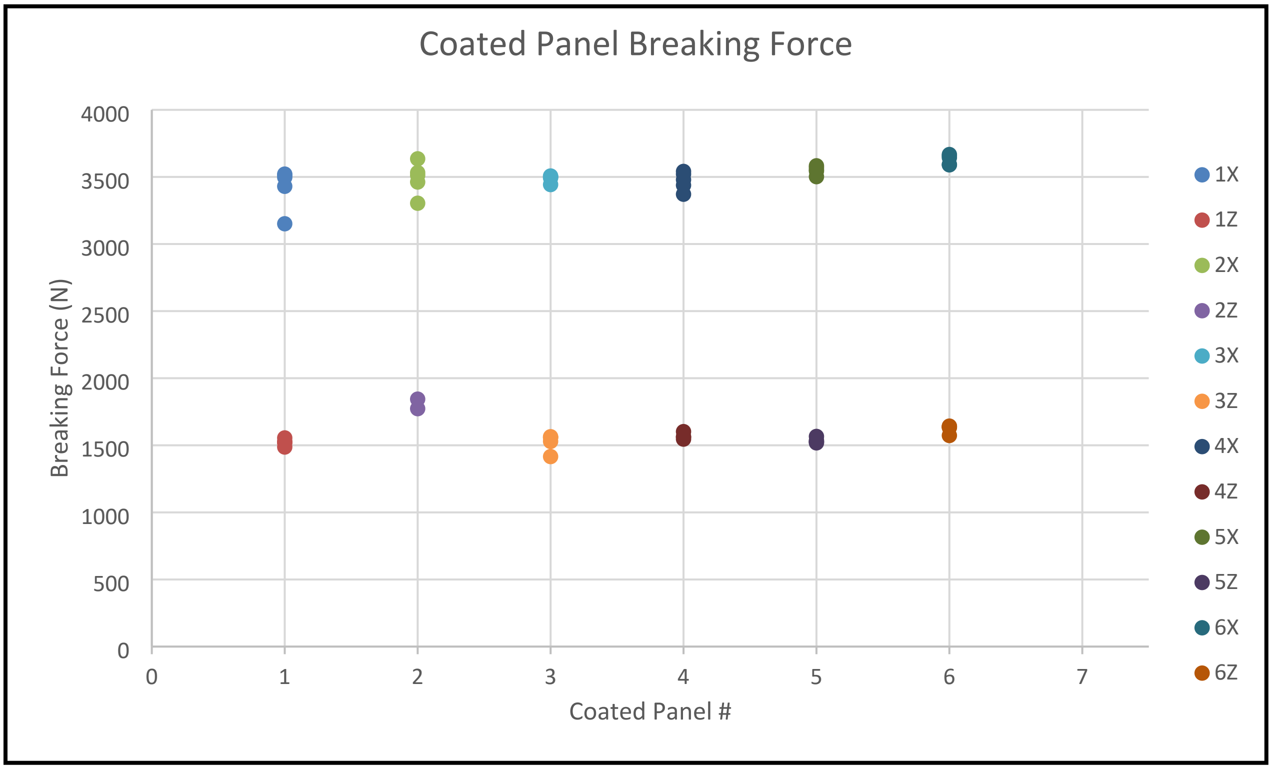

Figure 2: Coated panel breaking force for five different coatings with one control.

1.2.3 Design for Printing

After selecting a material and coating, the vehicle fairing designs needed to be modified for printing. To eliminate bead to bead porosity, encountered with multi-bead walls, it was decided that the final fairing designs would be printed as a single wall thickness. The bead dimensions, 0.25" wide and 0.05" tall, were used for the design. The existing vehicle panels could be modified for these printing dimensions and for the maximum printable size on the Cincinnati Incorporated BAAM systems in use at MDF. Maximum printable dimensions at ORNL are 240"x85"x75" and 143"x65"x100".

To print complex geometries with a single bead, the slicing process needs to be manipulated to create the proper toolpaths. The way contour paths are generated involves an offset step from the outside into the center of the object to create a centerline for the toolpath. When an object is hollow, such as a donut, the offsetting happens from both sides of the hollow object because it has two "outsides". These two offsetting steps will overlap for an object that is a single bead width thick. The result is a negative area from the overlapping offsets and ultimately no toolpath is planned. To overcome this limitation, the standard approach is to design the component, which ultimately needs to be hollow with a single bead wall, as a solid object and allow the slicer to do the hollowing operation. The slicing process will offset from the outside, of which there is only one now that the object is solid, to create the single outer bead. This single toolpath is the desired geometry for printing.

Using this design concept, Anduril was able to design all the vehicle panels for printing with a single bead wall. The set of vehicle panels is called a fairing set. ORNL printed the components and sent them to Anduril for coating and testing.

1.2.4 Additional Coatings and Reinforcement Research

After the first set of vehicle panels was made, Anduril installed them on a prototype vehicle for testing. Overall, the testing was a success and the vehicle performed as expected. Some breaking of the layer-to-layer bonds occurred in various scenarios including vehicle impacts. This renewed the interest in finding improved coatings and panel strengthening approaches.

Based on the method of failure, tensile strength was determined to be less important of a mechanical property than flexural strength. This meant a new round of testing needed to be conducted, using 3-point bending, to understand how the various panel preparation methods compare. In addition to testing panels with just a spray or roll-on coating, three new ideas were investigated: varying fiber load and resin type within the polymer, applying a fiber weave as a backing to the panel, and inserting fiber rods and resin to pockets.

For the change to the fiber load, tests were conducted with 0%, 10%, and 20% glass fiber, rather than the previously tested carbon fiber. The glass fiber has lower stiffness than carbon fiber, which should allow the panels to flex more and fail less. In addition to ABS, samples were tested with the addition of a thermoplastic polyurethane (TPU), which is a flexible resin. Blending the TPU with the ABS should improve the layer-to-layer bond and allow the panel to flex more without breaking, which should minimize the type of failures being experienced by the vehicles.

A fiber weave can be applied to all surfaces on the vehicle panels and should improve mechanical performance. Fiber weave, such as Kevlar and fiberglass, can be acquired inexpensive in sheets than can then be cut to size and applied to the panel with epoxy. This solution can easily be applied to the interior of the vehicle panels, even those with a complex geometry.

For the new design approach with pockets, a modification was needed to create a pocket that could contain resin or a rod. This approach was nicknamed Z-casting. With respect to the final vehicle panel design, rods/pockets cannot be applied everywhere. However, there are many places where they could be used, enough to make it valuable to test them and understand how they improve vehicle performance by adding them. Testing was conducted by inserting fiberglass rods to the pocket as well as simply filling the pockets with resin. A sample test panel with pockets can be seen in Figure 3, and a full list of the sample types can be seen in Table 2.

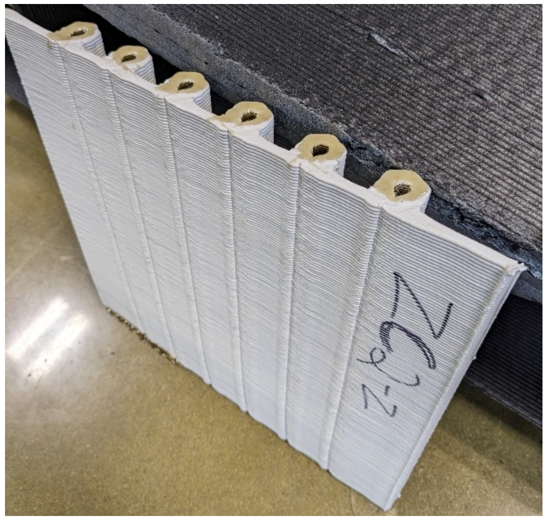

Figure 3: A test panel with pockets designed on the backside (inside of the vehicle) to inject epoxy or fiberglass rod.

Table 2: List of all sample types for flexural testing.

Varied fiber loading	
FL1	ABS (0% GF)
FL2	ABS (10% GF)
FL3	ABS (20% GF)
Material testing	
MT1	40% ABS/GF + 60% TPU
MT2	60% ABS/GF + 40% TPU
MT3	80% ABS/GF + 20% TPU
Coatings (using ABS w/ 20% GF)	
CO1	Epoxy
CO2	Vinyl Ester
CO3	Polyurea
Reinforced coatings (using ABS w/ 20% GF)	
RC1	Fiberglass cloth - 9 oz/sq.yd twill weave (5 layers @ .009")
RC2	Kevlar cloth - 5.3 oz/sq.yd twill weave (4 layers @ .011")
Z-casting (using ABS w/ 20% GF)	
ZC1	Epoxy
ZC2	Vinyl Ester
Reinforced Z-casting (using ABS w/ 20% GF)	
RZ1	Fiberglass rod
Pressure test	
PT1	ABS (20% GF)
PT2	60% ABS/GF + 40% TPU

1.2.5 Mechanical Testing

After all the samples were prepared, flexural and breaking strength tests were conducted on bar shaped samples that were 2” wide and 15” long. Testing was via 3-point bend on a 22kip capacity machine with 12” spacing between pins. Testing was conducted on samples at low speed, <0.1in/s, and high speed, 30in/s. The results can be seen in Figures 4 and 5.

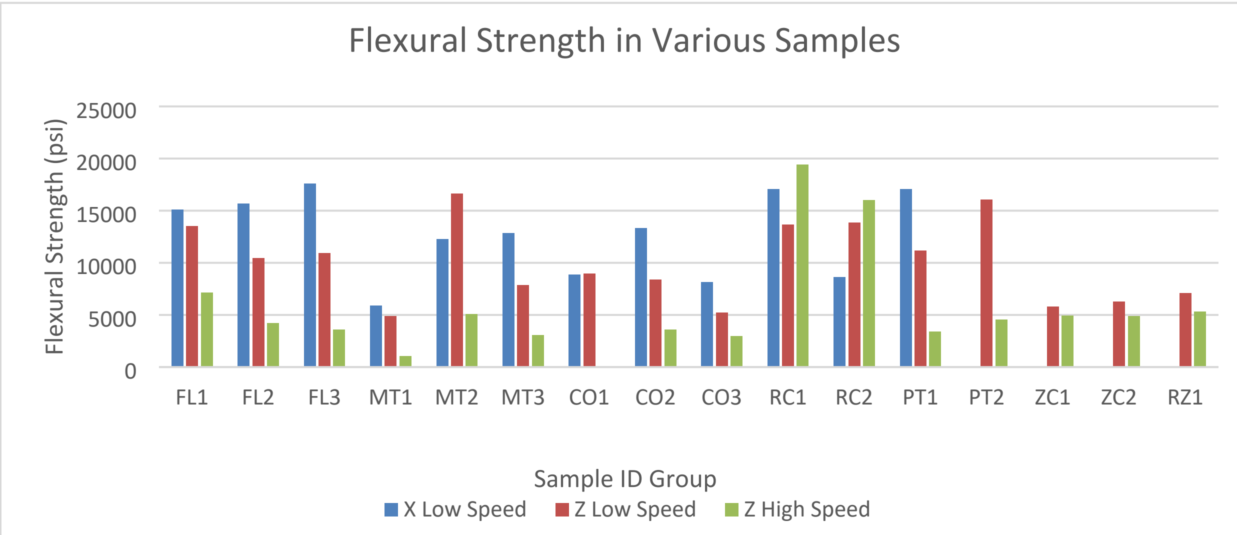

Figure 4: Flexural strength from 3pt bend testing.

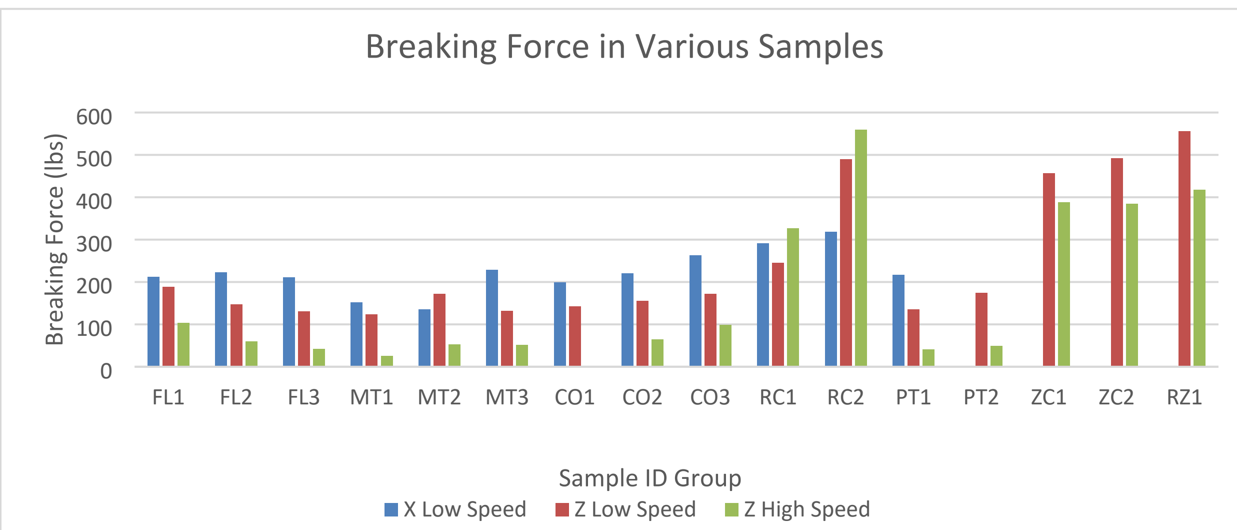

Figure 5: Breaking force from 3pt bend testing.

1.2.6 Final Fairing Production

Using the data from the mechanical testing, it was determined that the most useful approach for printing a fairing set would be to use the Kevlar weave coating. Anduril and ORNL worked together to iterate on the redesign of the fairings to accommodate the adhesive and Kevlar fibers. The fairings were printed with the normal printing parameters, Kevlar fabric was cut to size for the inside surfaces, then the interior printed surfaces were coated with epoxy and covered with Kevlar. A total of six pieces were printed with the new approach to complete an entire fairing with the improved strength from Kevlar. Figures 6-8 show the various components after the Kevlar fiber has been applied.

Figure 6: Fairing components with Kevlar fiber.

Figure 7: Interior of a fairing component with Kevlar fiber applied.

Figure 8: Fairing components with Kevlar fiber.

1.3 IMPACTS

This research conducted a significant amount of testing of various coatings and reinforcement methods for underwater vehicle design. The results of the mechanical testing of these samples can be much more broadly applied to better understand how to improve the performance of large format 3D printed parts. With the data and lessons learned on this project, Anduril has been able to commercialize the technology and being production of their underwater vehicles. The technology developed at ORNL, and the printing approaches for the BAAM, have been transitioned to industry and are in use today by Additive Engineering Solutions (AES) in Akron, Ohio. AES is printing more vehicle components for Anduril and continuing the development of new prototypes.

1.4 SUBJECT INVENTIONS

NA

1.5 CONCLUSIONS

This project was able to successfully go from the concept of a 3D printed underwater vehicle to a completed and fully functional vehicle. The researchers were able to successfully down select to a resin for the printing process to meet the mechanical loading requirements. From there, coatings were tested underwater at pressures up to 9000psi, then tensile tested to understand how the mechanical performance improved. The full set of vehicle panels was design optimized for the large format printing process and manufactured at ORNL. Additional research tested coatings, fiber weave reinforcement, and a new Z-casting approach to add pockets and further improve the mechanical performance. The success of this research resulted in a full vehicle, 3D printed with the technology from this project, as seen in Figure 9.

Figure 9: A 3D printed underwater vehicle.

2. ANDURIL BACKGROUND

This project started as a partnership between ORNL and Dive Technologies. Dive Technologies was a veteran-owned small business designing and building a next-generation, low cost, rapidly producible Large Displacement Unmanned Underwater Vehicle (UUV). Dive's goal was to leverage additive manufacturing and proven commercial off-the-shelf (COTS) subsystems to increase UUV capability while lowering production cost.

During the project, Dive Technologies was acquired by Anduril Industries. Anduril is a large business focused on autonomous systems. They develop a variety of products geared towards defense applications and work closely with the U.S. Department of Defense.