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Evaluation of Ship Board Additive Manufacturing: Final Report

April 2014

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EVALUATION OF SHIP BOARD ADDITIVE MANUFACTURING: FINAL REPORT

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ABSTRACT

Additive manufacturing (AM) is a rapidly emerging technology that has the potential to revolutionize modern manufacturing. Within the Navy, AM is being investigated for use in land based environments in rapid fabrication, legacy part development and repair, fabrication of custom tooling, rapid prototyping, and novel designs with complex internal geometries. There are a wide range of materials from polymers to metals that can be used in AM. The ability of additive layer manufacturing to rapidly fabricate complex components enables unparalleled design freedom and design optimization that can change traditional manufacturing and design paradigms. Current use of additive manufacturing has been focused on controlled, land based environments. However, full exploitation of AM capabilities in a shipboard environment for Navy use can significantly enhance manufacturing agility. Inventory of parts can potentially be replaced with inventories of feedstock material. The objective of this project is to measure the impact (mechanical and geometric properties) the at-sea environment (temperature, humidity and vibration) has on manufactured parts. Our goal is to provide ONR a vision for understanding the potential for at-sea additive manufacturing and an understanding of the enabling technologies that must be developed before this is possible. This report provides a high level survey of the state of the art in additive manufacturing to help the reader understand the advantages and disadvantages of each process. This is followed by a summary of at-sea additive manufacturing experiments conducted in October of 2013. The goal of these experiments was to provide an understanding of the impact sea state conditions (humidity and ship motion) have on one additive process, Fused Deposition Modeling.

1. BACKGROUND

Additive manufacturing is commonly referred to as 3-D printing or direct digital manufacturing. It utilizes computer aided design capability to build components by depositing thin layers of material layer after layer from a digital blueprint. Additive manufacturing, like nature, builds structures layer by layer rather than by removal of material. This approach to manufacturing enables the synthesis of components and systems that have previously been impossible. The first additive processing systems based on Stereolithography (3D printing) were introduced in the late 1980's.[i] Today, there are many different approaches (Stereolithography (SLA)[ii], Selective Layer Sintering (SLS)[iii], Fused Deposition Modeling (FDM)[iv], Solid Ground Curing (SGC)[v] and Laminated Object Manufacturing (LOM)[vi] to name a few) for achieving the same purpose, constructing a part layer by layer. The primary advantage of additive manufacturing is that complexity is cost-free. Unlike traditional machining practices where you begin with a block of material and remove material to create your part, Additive Manufacturing decompose the part into layers and build the part layer by layer. Parts can be made with voids (reducing weight and material usage) and additional complexity does not waste material or cost additional machining time. In addition, parts can be quickly manufactured without the need for expensive tooling. The earliest systems focused on polymers and plastics. Today, there are numerous metal-based systems.

Current use of additive manufacturing has been focused on controlled land based environments. However, full exploitation of AM capabilities in a shipboard environment for Navy use can significantly enhance manufacturing agility. Targeted ships such as Military Sealift Command (MSC) to strategically position combat cargo/supplies and the Navy Bureau of Medicine and Surgery (BUMED) hospital ships could significantly benefit from rapid on-the-fly manufacturing to enhance warfighter capabilities and fleet readiness in theater. Identification of these potential disruptive benefits is currently being discussed within Navy Warfare Development Command. Through the Chief of Naval Operations Rapid Innovation Cell (CRIC) there is an upcoming experiment to examine 3-D printing at Navy facilities in Norfolk and San Diego for rapid fabrication of selected components. Similarly, Walter Reed National Medical Center has been using AM for custom medical tooling, prosthetics, custom implants, and surgical guides. Much of the investment has been focused on land based systems and there are significant challenges in understanding the gross ship motions and environmental effects on the additive manufacturing processes and component quality onboard ships. Unlike typical subtractive fabrication processes such as machining that focus on material removal, additive processes melt or soften material to form layer by layer fabrication. AM processes can be more severely affected by vibrations, ship motions, humidity, and potential contaminants that will lead to variation in component quality. The focus of this investigation is the impact at sea conditions (humidity and sea state) have on the performance of additive manufacturing system. In the following sections, we provide a high level comparison of the additive manufacturing processes. The goal is to provide the reader with an understanding of the advantages and disadvantages of each of the technologies within the context of deployment on a naval vessel. This is followed by an overview of ORNL and the Naval Surface Warfare Center (NSWC) Carderock Division at sea additive manufacturing experiments. We describe the tests that were conducted and results followed by suggestions for future work.

1.1 ADDITIVE PROCESSES

Figure 1 shows the breakdown of the various additive manufacturing technologies. We start by differentiating the feedstock between metals and polymers. One important element not captured in the figure is support material. The term "support" defines how the technologies support overhanging structures (cantilevered over open space). For example, vat polymerization and powder bed systems support overhung structures with uncured liquids and unmelted powders respectively. The general advantage of these technologies is very little waste. The unmelted or uncured material can be reused leading to only using material that goes into the final product. Extrusion technologies (FDM) use either break away or soluble support. Therefore, there is material that is wasted during the manufacturing process. An analysis of over 800 builds at ORNL shows that the amount of support ranges from less than 0.2% of the model material to over 4X the amount of model material with an average of 31%. In all cases, there is work that must be performed in removing the support material. For vat polymerization, the parts must be cleaned and cured with gloves for personal protection. For powder bed systems, the part must be removed from the powder bed and the powders must be filtered before reintroducing into the machine. In the case of most laser powder bed systems, the powder is loose and part removal is easy. However, the powder is loose because, during the manufacturing process, the powder bed is maintained at a relatively low temperature. This has advantages and disadvantages. The advantage is easy part removal. The disadvantage is large temperature gradients during the manufacturing process which manifest themselves as residual stress leading to warp and curl. Arcam's e-beam powder bed system maintains a very high temperature in the powder bed (approximately 700 C) sintering the powder and minimizing residual stress. This reduces warp and curl in the part but makes powder removal a little more labor intensive. In some cases, laser polymer powder bed, the unmelted material is not reusable.

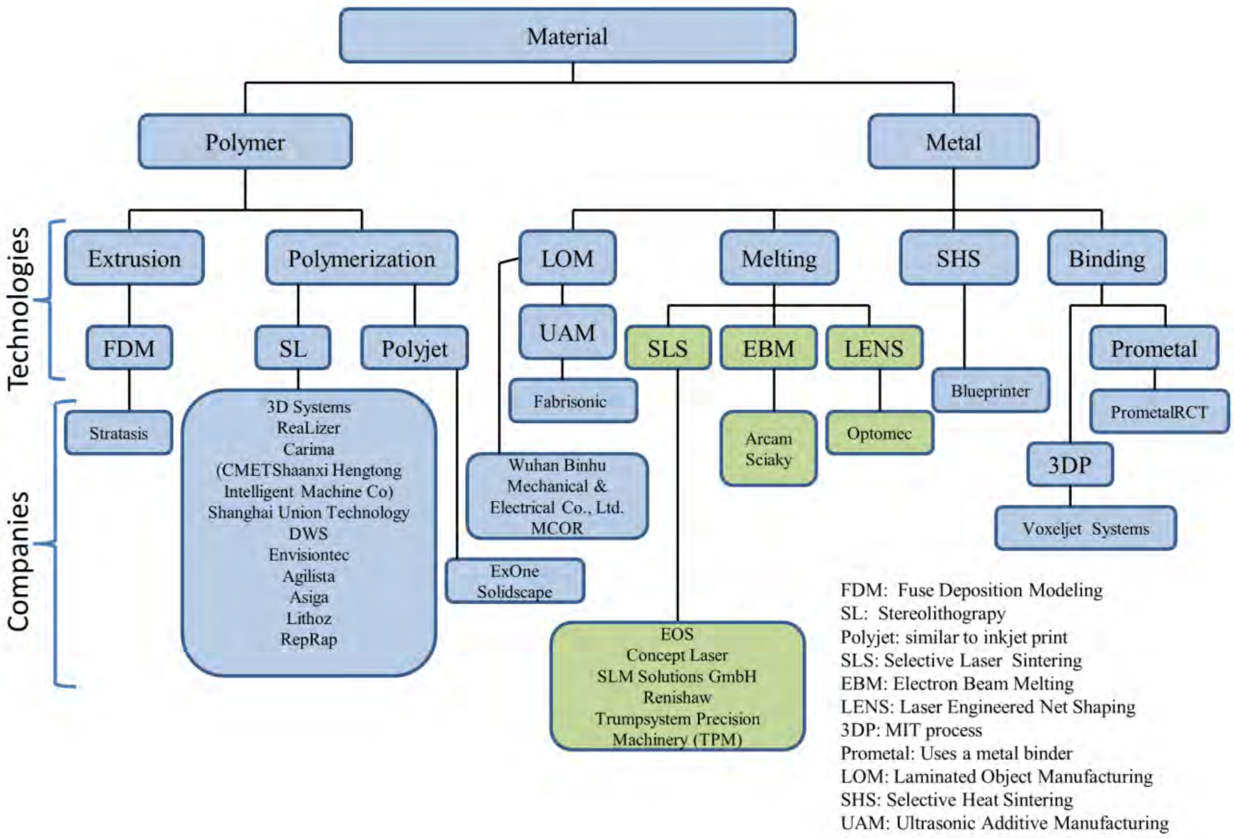

Figure 1: Overview of technologies

1.1.1 Polymer Overview

In the area of polymers, there are three basic methods of manufacturing a part: *extrusion*, *polymerization* and *binders*. The most popular extrusion technology is the *Fused Deposition Modeling (FDM)* developed by Stratasys. This technology uses a polymer wire as a feedstock and extrudes the material through a nozzle to manufacture the part. Stratasys has a number of different systems ranging from under $10K (Mojo and uPrint) to high end manufacturing systems costing up to $450K (Fortus 900). In addition, Stratasys has a very strong materials research group exploring a wide variety of materials with different material properties. Their traditional materials included ABS, Polycarbonate and Ultem 9085. Emerging materials include nylons, Ultem 1010 and carbon fiber reinforced materials.

Vat polymerization systems or material jetting use a UV light that hardens photopolymers to create the solid part. The conventional *stereolithography* systems (SLA) use a vat of material providing very high resolutions (under 0.003”) but are limited to a single material. Another process uses a *material jetting technology* that sprays a liquid photopolymer into a pattern that is then cured by a powerful UV light. The advantage of this technique is the ability to deposit a variety of materials over varying properties onto a single layer of a single part. However, in both cases, the photopolymers have inferior properties to the extruded thermoplastics, delegating the technology primarily to the prototyping industry. The final polymer system is a powder binder approach developed by Z-Corp. This technology uses a polymer binder to join powders creating the final part. Like polymerization, the advantage of this approach is the ability to deposit a variety of materials but the disadvantage is poor mechanical properties.

1.1.2 Metal Overview

In the area of metals, there are basically three ways to grow a part: *lamination* (solid state fusing of layers of metal), *melting* (using lasers or ebeams to melt powder of wire) and *sintering* (using a binder to hold powders together and using an oven for the final sintering). Each of these technologies has advantages and disadvantages.

Lamination (Fabrisonic) uses an ultrasonic horn to bind thin sheets of metal together. The advantage of this technology is low temperature fusion of metals. Rather than melting the feedstock, the ultrasonic energy uses vibration to bind the layers. Since the feedstock is a foil of material, the system manufactures parts very rapidly but also has a subtractive component. The advantage of the process is it does not require an oven, is manufactured in an open environment, and therefore enables integration of electronic components (batteries, wires, sensors…) into the structure. The disadvantage is that the z-strength (layer to layer) is low, the process does not easily enable very complex structures (lattice, aggressive overhangs) and typically uses softer metals as the feedstock (aluminum, copper, bronze..).

Melting uses an energy source to melt the metal feedstock. The feedstock is typically a metal powder or wire (Sciaky) and the energy source is either a laser or electron beam. Sciaky uses an *e-beam wire feed* technology. It is similar in principle to the fused deposition modeling but uses a metal wire feedstock and electron beam rather than melting a thermoplastic wire and extruding it through a fine nozzle. The advantage of this technology is the ability to make large metal parts fast. The wire feedstock also is relatively easy to control (no powder cleanup). The disadvantage is the high residual stress in the parts. Most of the other metal melt technologies use powders as the feedstock and lasers or electron beams as the energy source. Another differentiator is the use of a powder spray or a powder bed. *Metal powder spray* systems spray the powder out a nozzle and melt the material at the part interface. The advantage of this technology is the ability to blend or change powders within the part. The disadvantage is the lack of support which restricts the complexity of the part. Most powder feed systems find applications in the coating applications (putting a hard metal coating over an existing part). The most popular metal powder bed system is the *laser powder bed*. Companies such as Renishaw and EOS deposit thin layers of metal powder over a platen and use a laser to melt the powder each layer. The unmelted powder serves as the support. The advantage of this technology is the ability to manufacture very complex metal parts. In addition, the laser powder bed systems maintain a relatively low powder bed temperature. They do not preheat the bed which saves time. The part is loosely suspended in the powder making part removal and cleanup relatively easy. There are many tradeoffs to consider. Finer detail is possible with finer powders and laser spot size. However, the finer detail means longer build times. Reducing the weld pool by a factor of 2 reduces the build rate by a factor of 8 so there is a penalty in terms of time for fine detail. Also, care must be taken when using fine metal powders. Renishaw suggests changing the filters every 60 hours of operation. The fine powders are pyrophoric so the filters must be wetted out before removal. Arcam has pioneered the *e-beam powder bed* technology. The advantage of the e-beam is it is possible to rapidly (microseconds) redirect the energy. Therefore, the e-beam system can have 50 to 100 weld pools running simultaneously. This helps not only with speed, but also reduction of thermal gradients and residual stress in the part. Arcam also uses the e-beam to preheat the powder bed. This slows the process but helps with containment of the powder and reduction of stress. In addition, it is possible to manufacture parts that are suspended in the powder without heavy mechanical support. This is not easily achieved with lower temperature powder beds that are susceptible to warp and curl in the part. The disadvantage is, since the powders are sintered, it takes more work to remove the material and break it up into a fine powder for reuse. The final metal technology is the *binder jet metal printing*. This is a three step process. Much like the polymer binder jet, layers of metal powder are laid down and a print head moves across to selectively spray on a binder solution. A heat lamp then dries the layer before another layer is deposited. Once the object is completed, it is placed in an oven to fully cure the binder. However, the part is held together with cured binders and is still fragile (green). The final step is to put the part in a high temperature oven where it is infused with a secondary metal (typically bronze). This results in a very solid object that his almost completely dense. The advantage of this process is speed, size and flexibility. The basic process can be used to make parts as well as sand casts. The disadvantage is the multi-stage process.

With all of these systems, the user must understand that there is more equipment than just the printer. For FDM, there is usually a solution bath for removal of the water soluble support. For e-beam powder bed, there is typically a sand blaster for removal of unmelted material. For laser powder bed, there is typically a wire edm to cut the part off of the start plate (the plate from which the part is manufactured on). For binder jet systems, there is typically an oven or kiln needed for curing the material and infiltrating with a secondary material.

1.2 AT-SEA EXPERIMENTS

There are numerous applications, as well as technologies, that can help the Navy while at sea. Our focus is not which technology is best for Naval applications but what are some of the technical hurdles limiting deployment. As a preliminary exploration of at-sea additive manufacturing, NSWC and ORNL coordinated a deployment of multiple polymer fused deposition modeling systems on two vessels. The intent was to identify what technical hurdles must be considered before full deployment. The AM systems were Stratasys uPrints and the vessels were the JHSV-2 and Stilletto (see Fig. 2 through 5). The first tests were conducted on the JHSV-2. One uPrint was located in the mission bay which was exposed to the environment (salt spray, high humidity, variable temperature) and the second system was deployed in the crew quarters (controlled environment). All samples used for characterization were manufactured in the more challenging mission bay. Over the course of three days, multiple test samples were manufactured under different conditions. Baseline experiments were conducted at ORNL, samples we fabricated at the dock as well as underway. There were five sets of samples:

- Type V dogbones for mechanical properties (see Figure 6 and Figure 7)
- Round tensile bars (see Figure 8)
- Short beam shear samples (see Figure 9)
- NIST test article for geometric accuracy (see Figure 10)
- Tomography samples (see Figure 11)

The Type V dogbone tests consisted of manufacturing five sets of three dogbones during each test. Each set was aligned in the x, y and z-direction to take into account the anisotropic nature of extrusion deposition. Five sets were arranged in the center and four corners of the build chamber. Each build would take approximately 30 minutes. These samples were manufactured to help identify variations in mechanical properties as a function of the environment. Round tensile bars were manufactured to provide redundancy in mechanical testing but provided to be ideal for geometric accuracy. The long, tall structure provided to be an excellent candidate sensitive to vibration. Short beam shear samples were likewise manufactured as another source for mechanical data. The intention of the NIST test article was to identify geometric variations. However, the round tensile bar proved much more effective at picking up motion sensitive disturbances. Finally, the tomography samples were simple geometric structures that could help identify interior features, non-destructively, that may be impacted by the environment.

Figure 2: JHSV-2

Figure 3: Stilletto

Figure 4: Crew area

Figure 5: Mission bay

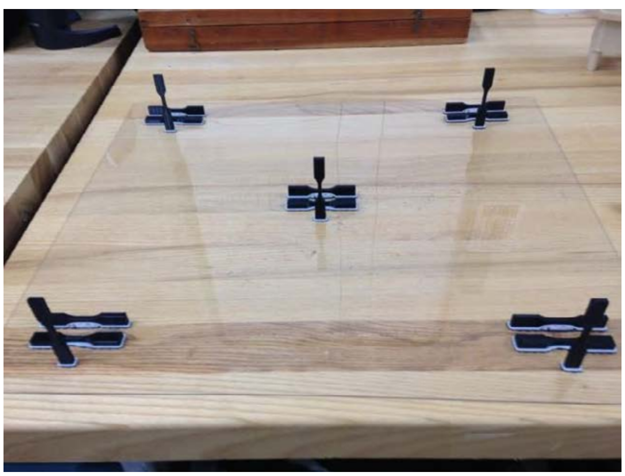

Figure 6: Five sets of dogbones

Figure 7: X, Y and Z type V dogbones

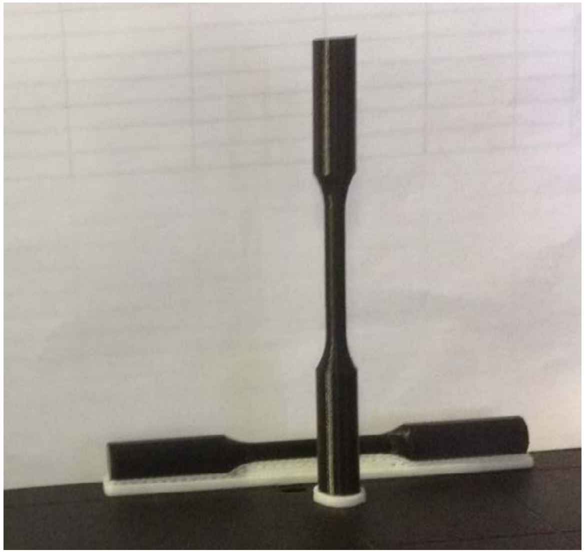

Figure 8: Round tensile bars

Figure 9: Short beam shears

Figure 10: NIST test article

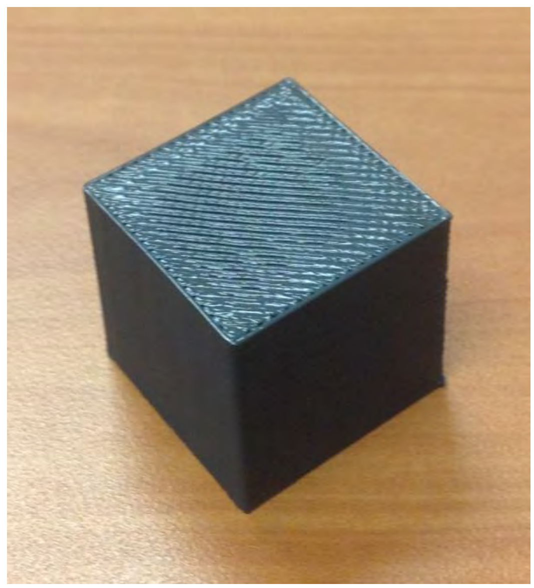

Figure 11: Tomography

1.2.1 Tensile Test Results

One of the objectives of the at-sea tests was to quantify the impact the sea state and environment had on the mechanical properties of additive manufactured parts. For the type V specimens, identical tests were conducted prior to deployment, at the pier, while underway and post-test (at the lab after tall testing). Each test had five samples (shown in Figure 12). Results are displayed in Figure 13 through Figure 15). In Figure 13, samples 1 and 2 while underway show a large discrepancy between all other samples. There is no present explanation for these results. Otherwise than those two samples, there was very little variability in the x and y direction strength when comparing pre-tests (at the lab), at the dock and while underway. However, the z-direction results show significant variability. There appears to be degradation in the z-strength from when the system was deployed to the final tests. The z-strength is typically the weakest of all directions due to porosity between layers and the deposition of hot material over the cooled prior layer. This appears to be exacerbated due to the ship board environment.

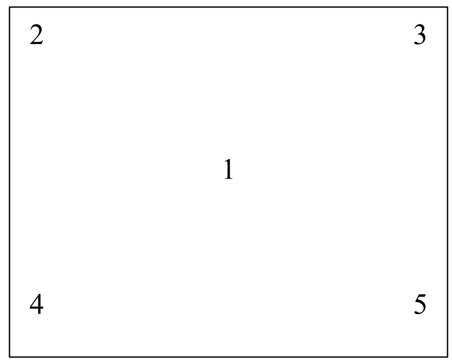

Figure 12. Build Plate Location Configuration Points

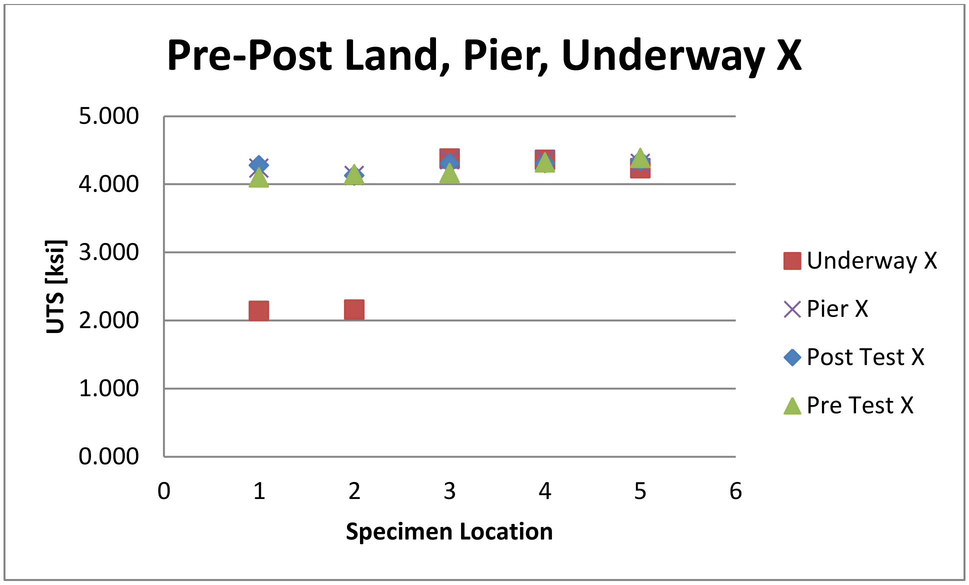

Figure 13: X tensile results

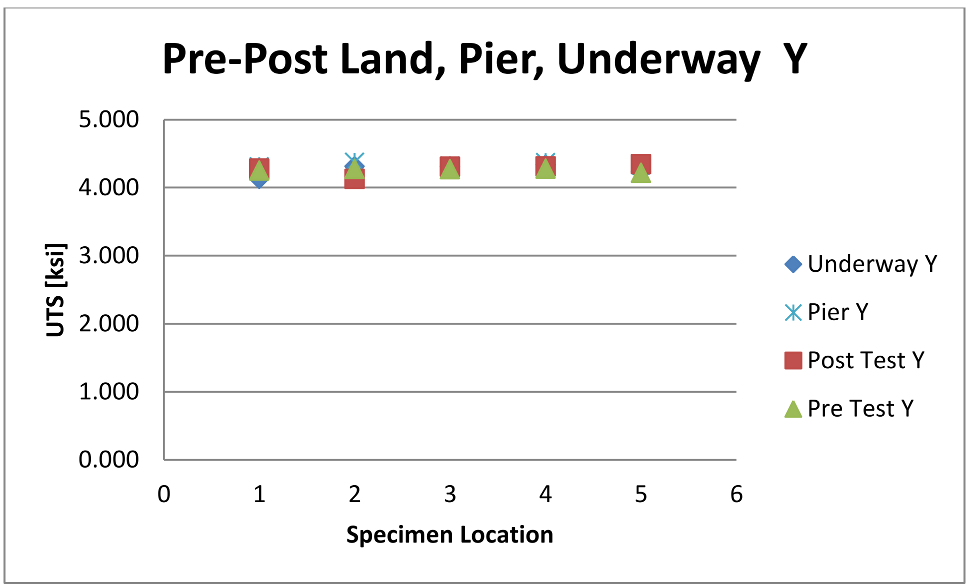

Figure 14: Y tensile results

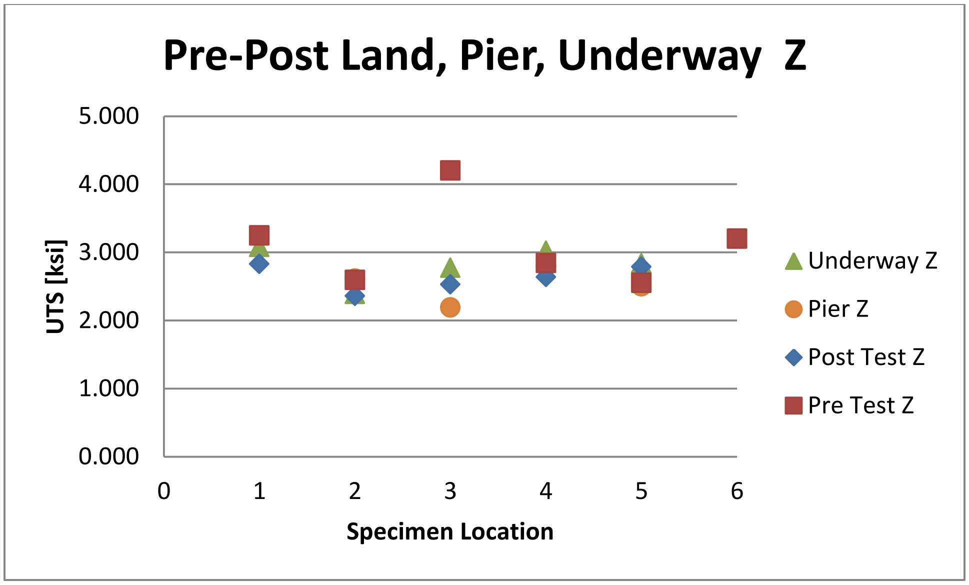

Figure 15: Z tensile results

1.2.2 Tomography Test Results

There are two environmental concerns with at-sea additive manufacturing: ship motion and humidity. High humidity has the potential to be absorbed by the feedstock material. If this happens, it will result in internal porosity during the manufacturing process. Moisture will boil off and result in embedded pores in the structure that will impact strength. Both cube and cylindrical elements were evaluated. Figure 11 shows a 1” cube (ASTM D3171 specimen) manufactured to investigate void content. Samples were manufactured on the JHSV-2 and characterized by NSWC. The results (shown in Figure 16 and Figure 17) show the internal porosity of the part. The relatively large gaps between extruded beads are the typical internal porosity associated with Fused Deposition Modeling. This porosity can be controlled by increasing the fill rate. However, the blown up region in Figure 17 has not been observed in other tomography tests conducted with parts manufactured in the lab. We hypothesize that this is an internal pore due to uptake of moisture on the filament when not properly stored.

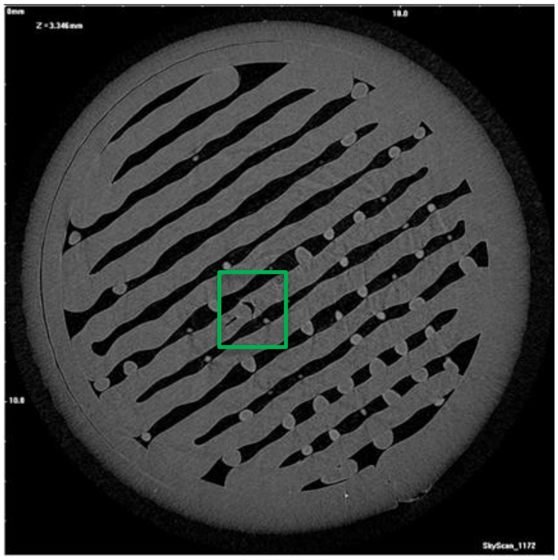
Figure 16: Void content


Figure 17: Internal porosity

1.3 IMPACT OF SHIP MOTION

The second area of concern was part quality during ship motion. Unfortunately, during the testing, sea conditions were not suitable for operations in significant sea states. However, samples were manufactured during transit between ports where the ship experienced both high frequency (engine) and low frequency (sea state) modes of vibration. Cylindrical tensile bars were manufactured during these excursions (shown in Figure 18 and Figure 19). The test articles had only one detectable flaw, a slight layer shift shown in Figure 19). This shift, approximately 0.010", was not detected on any other cylindrical specimens.


Figure 18: Cylindrical test specimen

Figure 19: Layer shift

Two sets of experiments were conducted to evaluate part accuracy during ship board manufacturing:

- Print multiple cylindrical tensile specimens
- Print the NIST test article

The round tensile specimens were tall, slender and geometrically simple. The NIST test article is short and geometrically complex. The hypothesis was that the combination of these two geometrical structures would span the range of parts that would be manufactured on a ship. Multiple specimens were manufactured before deployment, during deployment and after deployment to capture any condition related perturbations. A Faro ScanArm (shown in Figure 20) provided metrology measurements with an accuracy of +/- 0.0014 in for all specimens. The model for each specimen was compared to the measured point cloud to assess manufacturing accuracy.

Figure 20: Faro ScanArm

All parts manufactured during this project were scanned and compared to their original CAD model. Color coding on the model provide a visual representation of the magnitude of difference between the actual article and model where dark red shows a maximum positive deviation from the reference object to the actual object, green is where the nominal error is between +/-0.050 mm and dark blue shows the maximum negative deviation from the reference object. The part was printed and thermal supports were removed. Metrology equipment was calibrated prior to use. The part was scanned and rendered as a point cloud using parametric modeling software (GeoMagic). The point could was then converted to a polygon (as-is model) to facilitate the deviation analysis. The "as-is model" was aligned to the CAD object using a best fit method and then analyzed for deviations with the set input parameters.

1.3.1 NIST Test Article

The NIST additive manufacturing test artifact (model shown in Figure 21, printed part in Figure 22) was developed as a standard for evaluating the performance (geometric accuracy and surface roughness) of additive manufacturing systems. The model has many features that are typical in additive parts (round, concentric, holes, bosses, features in planes orthogonal to build direction..).

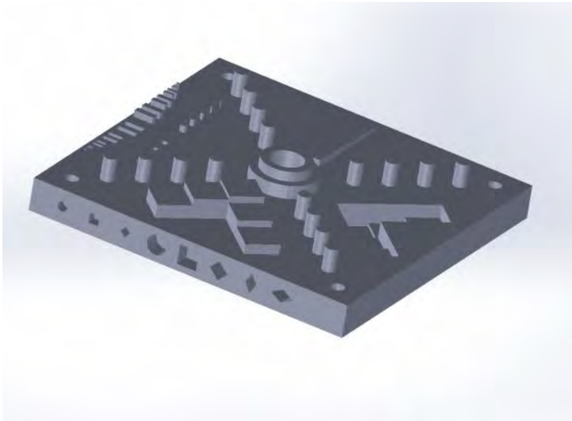

Figure 21: NIST additive manufacturing test artifact model

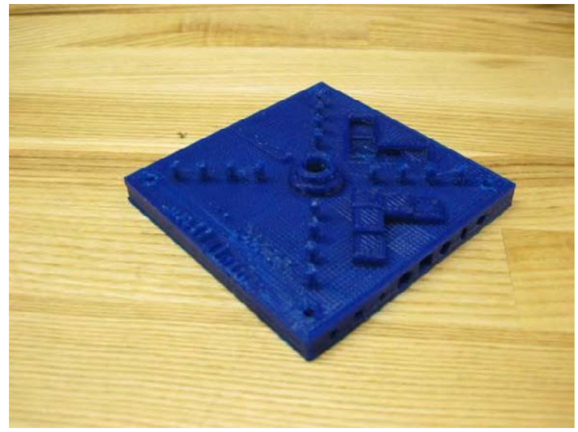

Figure 22: NIST test artifact

The sample analyzed (sample ID 4-6-1650) was the manufactured in the mission bay of the JHSV-2 while at the pier. The resulting overall analysis showed that part is slightly warped with a maximum upper deviation of 3.085 mm, maximum lower deviation of -4.899 mm with an average deviation of 0.0644/-0.311 mm and standard deviation of 0.1274 mm.

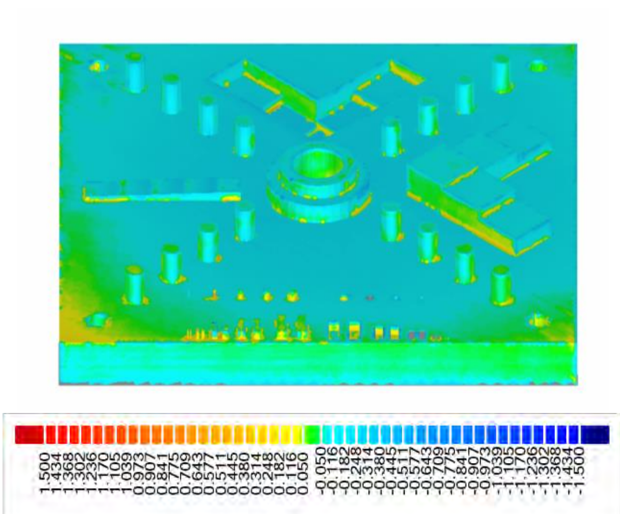

Figure 23: Closeness of fit on top

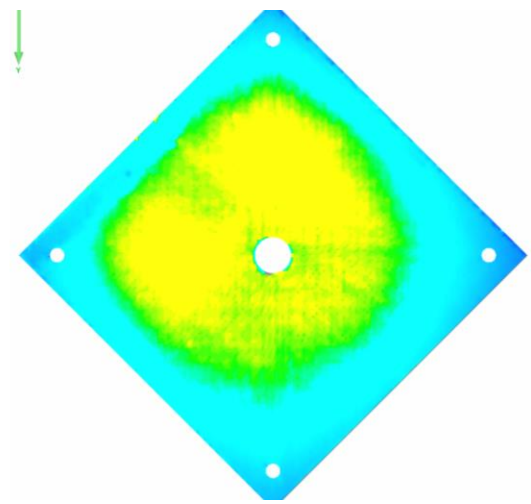

Figure 24: Closeness of fit on bottom

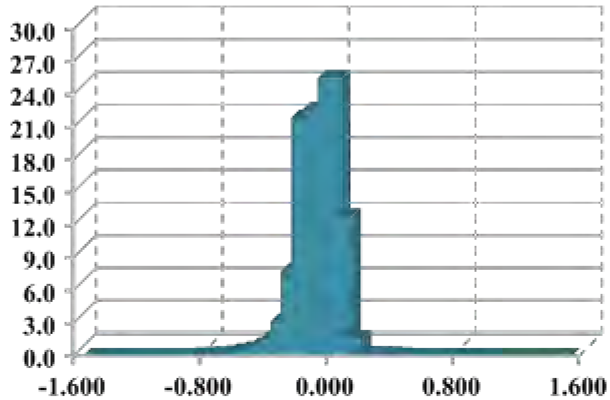

Figure 25: Deviation distribution

A 2D comparison through the XZ plane illustrates warping towards the outside of the part with an average deviation of 0.1159/-0.1818 mm and standard deviation of 0.1689 mm with 78.9% of the deviations within +/- 1 standard deviation. A similar comparison through the YZ plane shows that it is nominally precise but warps at the edges as well with an average deviation of 0.1159/-0.2477 mm and standard deviation of 0.113 mm with 58.6 of the deviations within +/- 1 standard deviation. A 2D comparison of the XY plane (the horizontal plane) shows that dimensions are slightly undersized with an average deviation of 0.050/-0.115 and standard deviation of 0.0605 with 82.8% of the deviations within +/-2 standard deviations.

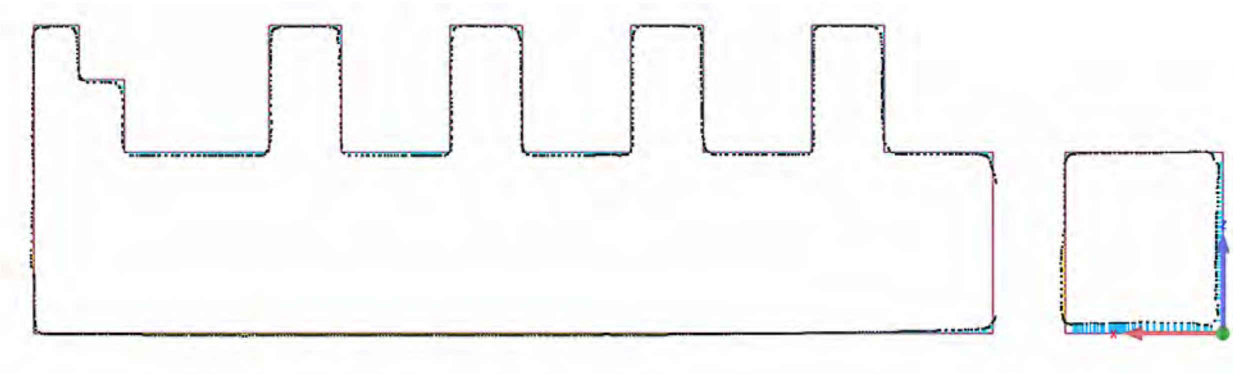
Figure 26: X-Z cross section

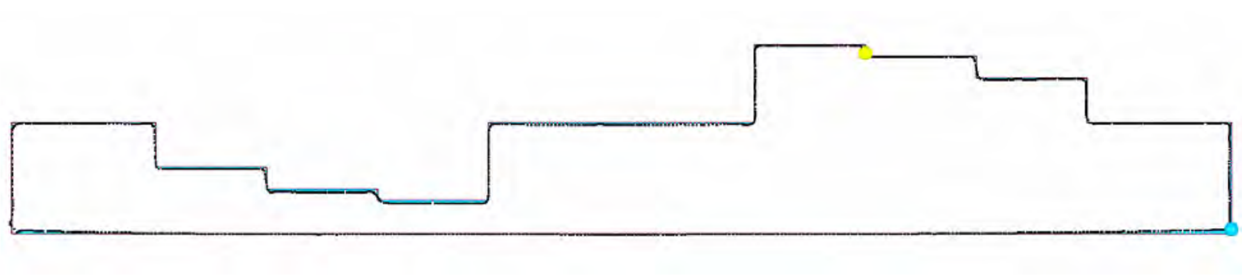
Figure 27: YZ standard deviation

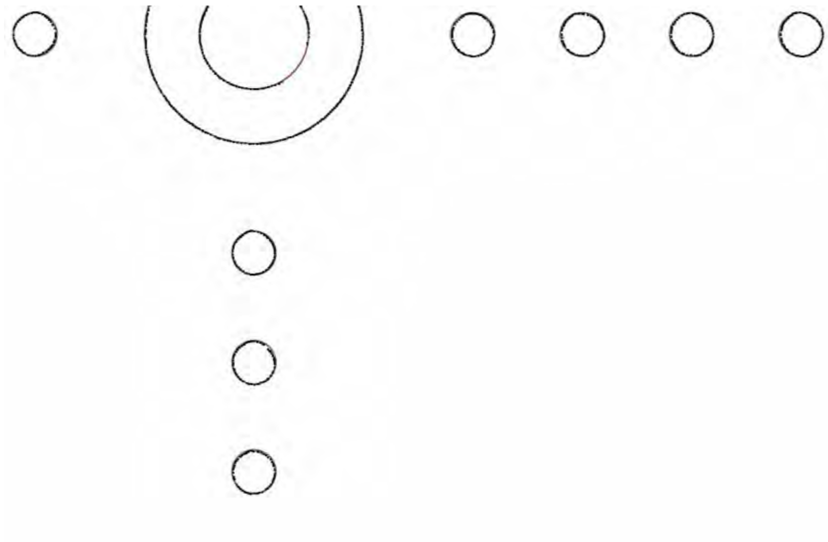

Figure 28: XY cross section

In summary, it is clear that the sample warped during manufacturing. This effect is less so in the XY planar direction but more apparent in the build direction (Z-direction). This effect may be caused by delamination between layers, poor cohesion to the substrate or swelling of the material.

1.3.2 Cylindrical Tensile Test Articles

A second set of specimens consisted of cylindrical tensile articles. These test articles were manufactured vertically with the test pattern displayed in Figure 12. These articles are geometrically very simple, tall and slender. The objective was to have a simple feature to analyze that was sensitive to ship motion. Three sets of test articles were manufactured. The first set was a pre-naval test run conducted in the laboratory at ORNL. The second set was manufactured on the Stiletto while in port. At the time of the experiments, the JHSV-2 was prevented from going out to sea due to a tropical storm. To emulate the motion that it may experience, the team elected to transfer the uPrint to the Stiletto, a much smaller vessel, docked in Norfolk. The motion of the smaller boat at the dock was significant enough to suggest a possible influence on the build accuracy. Three sets of test specimens were manufactured: the first control experiment was conducted in the laboratory, the second set of experiments were conducted on the Stiletto at the dock and the final tests were conducted at ORNL in the laboratory after returning from deployment.

1.3.2.1 Preliminary Tests

The preliminary runs provided a baseline measurement for the system's accuracy under ideal operating conditions. Five specimens were manufactured during this initial experiment and compared to the model.

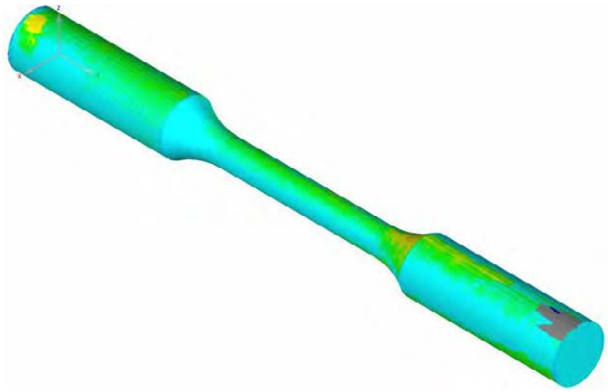

Figure 29: Cylindrical tensile specimen

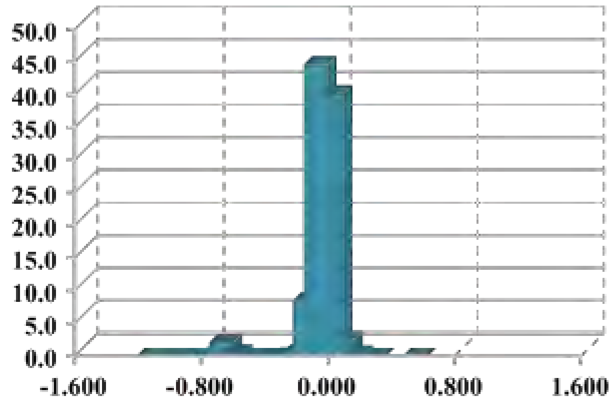

Figure 30: Deviation distribution

Table 1: Preliminary accuracy data

Sample	Max Upper Dev (mm)	Max Lower Dev (mm)	Average Dev (mm)	Standard Dev (mm)
Sample 1	0.1745	-1.0386	0.0330/-0.1452	0.0591
Sample 2	0.4178	-1.9264	0.0307/-0.0475	0.0567
Sample 3	0.2072	-0.9727	0.0277/-0.0517	0.0437
Sample 4	0.3136	-1.1045	0.0339/-0.0870	0.1171
Sample 5	0.1745	-1.0386	0.0330/-0.1452	0.0591

The results, tabulated in Table 1, show that the samples created before the deployment are mostly one standard deviation outside of the designated model. This effect was less so in the XY planar direction (cross section) than the build direction (z-direction).

1.3.2.2 Pier-side Tests

Due to adverse weather conditions, tests were limited to pier side. However, in order to maximize potential ship motion, the team transferred the uPrint from the JHSV-2 to the Stiletto, a much smaller vessel.

Table 2: Deployment accuracy data

Sample	Max Upper Dev (mm)	Max Lower Dev (mm)	Average Dev (mm)	Standard Dev (mm)
Sample 1	0.1871	-0.9558	0.0299/-0.0641	0.0474
Sample 2	0.2764	-1.0586	0.0331/-0.0599	0.0520
Sample 3	0.2464	-1.1329	0.0319/-0.0526	0.0581
Sample 4	0.2831	-0.7031	0.0237/-0.0576	0.0504
Sample 5	0.2574	-0.8275	0.0325/-0.0481	0.0561

Given the results, it is clear that the samples created aboard the Navy vessel are mostly within +/-1 standard deviation outside of the as-designed model. This effect is less so in the XY planar direction but does show some loss in cylindricity. Geometric integrity is well maintained throughout the samples.

1.3.2.3 Post Deployment Tests

A final set of tensile rods were manufactured at ORNL with the same equipment after deployment. The objective was to identify any adverse effects due to the deployment. Only 3 samples were manufactured during this evaluation.

Table 3: Post deployment accuracy data

Sample	Max Upper Dev (mm)	Max Lower Dev (mm)	Average Dev (mm)	Standard Dev (mm)
Sample 1	0.2203	-0.5625	0.0456/-0.0679	0.0479
Sample 2	0.2835	-0.4450	0.0802/-0.0701	0.0539
Sample 3	0.2983	-0.4795	0.0363/-0.0366	0.0351

Given the results, it is clear that the samples created after the deployment are approximately one standard deviation outside of the designed model. Comparing the three sets of experiments, there was not clear discrimination between pre-, during and post-deployment results.

2. CONCLUSIONS AND RECOMMENDATIONS

The experience of deploying an additive manufacturing system on a ship had some clear, and some “not so clear” results. In terms of clear results, the team was not only able to deploy and successfully run a commercial FDM system on a ship, but they were able to rapidly (under 3 hours to move and have running) transition the system from one vessel to the next. Therefore, it is clear that polymer FDM systems are at a mature enough level to be deployed and functional on a ship. A wide number of parts were manufactured in both conditioned and unconditioned space. It is also clear that care must be taken when handling the feedstock material. The high humidity environment can result in moisture uptake in the feedstock material. This moisture uptake can result in bubbling of the extrusion as the part is being manufactured. These internal bubbles could explain the reduction in z-strength observed during deployment. Cartridges purchased from Stratasys come in a sealed container with an internal desiccant. Once opened and installed in the system, there is not guarantee that the material will not absorb moisture. Therefore, care must be taken to minimize the humidity where the system is operating and properly store materials that have been opened. There was also no discernable degradation in mechanical properties expect in two instances: two questionable samples in the x-direction and a noticeable degradation in the z-direction during at-sea operations. The two questionable samples in the x-direction were extremely large (half the strength) whereas the other three samples showed no discernable differences. In contrast, the z-strength showed measurable changes (~10% reduction) regardless of sample position. In terms of impact due to ship motion, there was only two opportunities to experience any measurable sea states during transit between ports. One sample showed a slight shift between layers (0.010”) that could be caused by ship motion. Otherwise, the parts showed no discernable difference between land based manufactured parts.

In terms of recommendations, the team believes there needs to be a more thorough investigation of the impact of ship motion on additive manufacturing. This could be accomplished by a second deployment or outfitting an additive manufacturing system on a ship motion simulation platform to provide a more controlled experiment to correlation ship motion to part quality.

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