Advancing Metal Additive Manufacturing to Meet Naval Sustainment and Maintenance Needs

Final Report

Prepared under:

**NCMS Project No. 142264 and
Cooperative Agreement HQ0034-20-2-0007
for the
Commercial Technologies for Maintenance Activities (CTMA) Program**

December 2024

**National Center for Manufacturing Sciences
3025 Boardwalk
Ann Arbor, Michigan 48108**

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Acronyms and Abbreviations

Term	Definition
AM	Additive Manufacturing
C	Celsius
CRADA	Cooperative Research and Development Agreement
CTMA	Commercial Technologies for Maintenance Activities
DOD	Department of Defense
DON	Department of Navy
HMI	Human Machine Interface
ITX	Integrated Training Exercise
LMJ	Liquid Metal Jetting
MRO	Maintenance, Repair, Overhaul
NCMS	National Center for Manufacturing Sciences
NPS	Naval Postgraduate School
ODASD-MR	Office of the Deputy Assistant Secretary of Defense, Materiel Readiness
PCB	Printed Circuit Board

1. Executive Summary

Supply chain challenges are real, and that has impacted both defense and commercial establishments. Critical part shortages can cause significant manufacturing delays and cripple American businesses. If critical parts are not available at point and time of need, downtime and delays can quickly compromise mission goals, revenue streams and lead to loss of jobs. Additive manufacturing (AM) technologies have the potential to provide solutions which are more aligned with effective and efficient operation and supply chain metrics. This can be translated into on-demand supply of parts, at point manufacturing where parts are needed, quick turnaround and low-cost parts, keeping high machinery uptime and easy deployability, to name a few.

AM is a technology which uses digital design input to create, print, and produce a part in layer-upon-layer fashion. Metal AM, which is a subset of AM technologies, has shown potential and the capability to produce parts with enhanced design freedom as compared to traditional manufacturing (e.g., casting and machining). This enables quicker design iteration in the prototyping phase at lower cost and can be used to manufacture parts on demand at any given location. However, with all these advantages AM is still evolving and has its own challenges. Firstly, there are variety of metal AM technologies with varying degree of safety, adaptability, skill needs, capital expenditure, post processing needs and cost per part. Among all the commercially available technology, liquid metal jetting (LMJ) had demonstrated capabilities that positioned it to be an attractive metal AM solution for easy deployability both at sea and on land.

A proposal for a collaboration between the Naval Postgraduate School (NPS) and industry was proposed. The objectives of the collaboration were the following:

- Reducing the risks of deployment in varying operational conditions
- Advancing AM usage by identifying operational use cases including aboard ship, expeditionary bases, and shore facilities
- Advancing the knowledge of Department of Navy (DON) entities around AM and its applicable usages with an emphasis on forward deployment sustainment and maintenance

With a goal to educate, train and evaluate the technology, support was provided to install, commission and service both the machine at NPS and aboard ship. Team members from ADDiTEC's service, engineering and materials science visited naval establishments to support and interact with the NPS and Naval personnel. During these interactions, deployability was assessed and performance at sea was undertaken during underway in Hawaii. Feedback from ship was received and certain functional features were added to improve usability of the machine. Also during the project, the material portfolio was increased to three aluminum alloys that can be printed using LMJ technology. Following is the summary of upgrades during project duration:

- Onsite engineer support
- Upgrading machine software to enable
  - Auto drop mass calibration
  - Enable chiller leak detection
  - Enabling printing more than one custom recipe
  - Slicer upgrade
  - Bed temperature ramping up feature

  - Double chevron and optimized print opt to support 6061
  - Builder upgrade with significant user interface changes (profile display on the top right corner, file name carries forward when trying to save the main program file, etc.)

- Enhancement of material portfolio
  - Enable F357 alloy printing
  - Enable 6061 alloy printing

- Hardware upgrade
  - Use of 17-4 Steel build plate to increase usage life
  - Chiller leak detection
  - Hight temperature flexure build plate configuration for better thermal control

- Training NPS students and sailors from ship on LMJ printer

Funding was secured for the collaborative initiative through the National Center for Manufacturing Sciences (NCMS) Commercial Technologies for Maintenance Activities (CTMA) Program and the Office of the Deputy Assistant Secretary of Defense, Materiel Readiness (ODASD-MR).

1.1 Results

During this project, other than regular maintenance, service calls, consumables and spare parts support, many key technological features were enabled to advance the process capability. The following are the highlights:

- Installation and commissioning of two LMJ printers
- Training and educating students, personnel of NPS and Navy
- Providing onsite process engineer support
- Upgrading machine software to enable process features (e.g., leak detection system and automated calibration)
- Enhancement of material portfolio (adding F357 and 6061 Aluminum alloy)
- Hardware upgrade to support operational features (high build plate temperature printing to support 6061 printing)

Multiple enhancements were added to the ElemX machine (as listed in section 3.4) to improve its performance, overall capability and deployability at sea.

1.2 Benefits

To meet the challenges of the supply chain of critical parts, distributed manufacturing is an option which has been considered as a strategy to mitigate the risk. By having a technology like LMJ, it adds a reliable tool to the kit for manufacturing on demand capability. By meeting the objective of this project/initiative, data show that it is possible to have a technology that is easy to deploy with minimal infrastructural requirements, practically at any location (with limited modification), manufactures parts which is quicker and cheaper than contemporary technologies and much quicker to train those with basic machine trade skills to operate the machine. These initial advantages are critical for industrial manufacturing, to shore up supply chain resiliency and reduce the risk of loss due to disrupted supply chains.

Any technology which can be forward deployed is an advantage for the Department of Defense (DOD). It improves the readiness of the forces and reduces the dependency on supply chain fluctuations. Studies and trials with LMJ technology point to the fact that the technology is suitable for on board, on demand manufacturing, which translates to safer (when compared to metal powder AM technologies), easier (easy to learn and operate the printer), rapid prototyping and produce direct parts (faster print to parts in hand and quicker iteration, if design changes are needed). Incorporating the successful results derived from this project allows the DOD to improve readiness by increasing the overall throughput and reduce the cost of maintenance and sustainment errors, which will ultimately improve and better support the readiness of all Navy ships.

1.3 Recommendations

It is relevant to mention that the industry partner at the time when this project was initiated was Xerox corporation. Xerox divested its LMJ division to Additive Technologies LLC (ADDiTEC) around July of 2023. Nevertheless, key personnel involved remained with the project until completion. It will be important to recognize that ADDiTEC continues to make improvements in LMJ technology and brings additional value with their expertise in directed energy deposition and intent to advance AM using hybrid manufacturing and robotics.

It is recommended to continue collaboration with ADDiTEC on advancing LMJ technology for AM and the Navy’s technological needs. It is envisaged that further advancement in the technology can bring in following benefits:

- Reduced machine cost and footprint
- Hight temperature printing, opening printable material portfolio
- Use of robotics and hybrid concept to increase productivity and application space

1.4 Invention Disclosure

☐ Yes Inventions ☒ No Inventions

DD882 Invention Report sent to NCMS ☒

1.5 Project Partners

- Naval Postgraduate School (NPS)
- ADDiTEC (formerly Xerox)
- National Center for Manufacturing Sciences (NCMS)

2. Introduction

2.1 Background

Critical part shortages can cause significant manufacturing delays and cripple American businesses. If critical parts are not available at point and time of need, downtime and delays can quickly compromise mission goals, revenue streams and lead to loss of jobs. Innovations which allow agile responses to supply chain issues allow businesses to keep operating and allow the economy to stay healthy. The DOD faces similar challenges and in January 2021, the DOD published its first ever AM strategy to "provide a shared set of guiding principles and a framework for AM technology development and transition to support modernization and warfighter readiness" across the military. The versatile technology has already significantly impacted industrial production as the world shifts from analog to digital technology and is increasingly being seen across the DOD as a powerful and versatile tool providing technical advantages across a range of defense applications.

For metal AM to fulfill the needs of the DOD's AM strategy including modernizing national defense systems, increasing material and operational readiness as well as enhancing warfighter innovation, metal AM solutions must be able to operate in a distributed manufacturing manner and be deployable at strategic point locations both at sea and on land. The ability for metal AM systems to be deployed at sea is critical for Navy maintenance and sustainment as it provides the ability to produce one-off parts without the need of storing these parts on the ship and can provide the ability to rapidly repair damaged components, reducing downtime of critical Naval equipment. The same can be said for forward deployed locations on land, where warfighters should be able to sustain equipment in the field for lengthy periods of time while potentially being cut off from supply chains. For metal AM technologies to meet such requirements, they must be fast, simple, safe, and deployable. Metal AM technology has struggled in this space due to infrastructure requirements, advanced expertise and secondary processes needed to establish a seamless file to part-in-hand workflow. Recently LMJ technology has entered the metal AM market and has demonstrated capabilities that position it as an attractive deployable metal AM solution for environments both at sea and on land forward locations. This initiative will focus on two principal areas of accelerating the adoption of LMJ in the DON: The first focusing on enhancing the deployability of the technology; the second on establishing AM education hubs, both needed to enable parts-on-demand printing for maintenance, repair, and overhaul (MRO) applications.

2.2 Purpose

The primary purpose of the project was to introduce and establish AM technology in the form of LMJ printing within Naval establishment by installation/commissioning of printers and educating and training research/active-duty personnel. This was followed by evaluating printing performance at sea and based on operation feedback, implementing modification/enhancement to support adaptability and deployability of the technology. The overall objective was to assess the capability of using LMJ technology when forward deployed and assess associated education needs. Focus being:

- Reducing the risks of deployment in varying operational conditions
- Advancing AM usage by identifying operational use cases including aboard ship, at expeditionary bases, and at shore facilities

- Advancing the knowledge of DON entities around AM and its applicable usages in the Navy with an emphasis on forward deployment sustainment and maintenance

2.3 Scope/Approach

The project had two main initiatives. The first focused on enhancing the deployability of the LMJ technology; the second focused on establishing AM education hubs to enable parts-on-demand printing for MRO applications. The two initiatives are outlined following:

1. Initiative 1 – Deployability: Assess the rapid field deployment of LMJ technology (ElemX), by examining environmental impacts on part quality (e.g., onboard motions, vibrations, temperature, humidity, etc. and executing on required modifications to hardware and software to address these extreme conditions, including developing part design/process planning software to achieve desired quality under varying conditions. This project was executed in concert with the AM Education Hub(s) Project, where there will be an “on land” ElemX to compare results of printing under different conditions, and in concert with the Materials and Quality Project, that will drive the development of new materials and quality prediction/control technologies.
2. Initiative 2 – AM Education Hub(s): Using DOD maritime settings as a surrogate for austere industry applications, this project will assess responding to immediate parts needs and leverage the work to educate the force on how AM can help address supply chain issues and optimize maintenance operations. It will include identification of parts suitable to be manufactured with AM (and specifically with the LMJ technology). Each Hub will also serve as a learning center to educate DON personnel on AM usage.

It is to be noted that both initiatives were taken up as a parallel effort. The approach was such that both the printer would mirror itself in performance and operation. This will identify potential issues that may have occurred due to changes in operating conditions (vis-à-vis land and sea).

3. Project Narrative

3.1 Cooperative Research and Development Agreement (CRADA)

By the last quarter of 2020, NPS and ADDiTEC (formerly Xerox) decided to collaborate under a CRADA. The goal was to use ElemX liquid metal printer to additively manufacture Aluminum alloy components suitable for the Navy. Under this agreement, the following were provided by the industry partner:

- Technical support and adjustments to the ElemX liquid metal printer
- Initial training on printer usage and setup
- New material samples for evaluation when available
- Maintenance requirements and reconfiguring of the ElemX liquid metal printer at the NPS location as needed

The ElemX machine was installed at NPS on February 3rd, 2021. Figure 1 shows the installed machine at NPS. After installation, students were trained on machine operation and basic maintenance. This machine was used for a master's thesis[1] that focused on material property characterization of printed Aluminum 4008 alloy wire. The student who worked on the thesis was Lt. William Kimberl. During his thesis work ADDiTEC's (then Xerox) service and process team visited NPS to train and troubleshoot machine related issues. The service team from ADDiTEC ensured the machine was operational and available to students. Research data and results are published in the master's thesis dated June 2022.

Lt. Kimberl's research generated lot of interest within the Naval community and provided relevant feedback to the ElemX team to improve upon the machine's software and hardware design. The study proved that machines like ElemX which is quick to install, easy to train and had open enough architecture for future improvements, might be well suited for at sea or front-line deployment. Based on the outcome of the work done under CRADA, installation of a second machine occurred onboard ship that was tested for sea trials during a two-week underway.

Figure 1. ElemX Machine at NPS

[1] Mechanical and microstructural properties of Al-4008 produced by Additive Manufacturing via Liquid Metal Printing – William C. Kimberl V, 2022

3.2 AM Education

Based on the positive outcome of the CRADA, a concept paper was drafted by NPS, to define a proposal to advance metal AM to meet Naval sustainment and maintenance needs. In accordance with the proposed initiatives in the paper, engineering and service support to NPS was contracted with the industry partner. In this initiative the goal was to create an AM education hub at NPS for the Navy, where Naval personnel can be introduced to AM and trained in the craft. The effort also was to create an awareness about the technology and the benefits it brings to public and DOD by reducing the impact of supply chain fluctuation for critical parts.

Between June and August 2022, the following activity was supported by the ADDiTEC team:

- Supplied 03 prototype build plate removal system without overhead crane
- Provided software update
- Provided advanced training for student/sailors
- Relocated ElemX printer to a new lab

The plate removal system was customized to comply safety when the printers are deployed at sea. Figures 2 and 3 show the difference between the actual build plate removal system and the modified one for Navy.

Figure 2. Build Plate Transfer Using Sky Crane and Gripper Assembly

Figure 3. Stationary Build Plate Transfer System for Navy

The software update provided improvement in part quality and fixing of existing bugs. Along with six monthly maintenances, students were provided advanced training to maintain and troubleshoot printer issues. This was also the time when ElemX had to be moved to a lab inside NPS (Watkin's Hall). The new location inside NPS for ElemX is shown in Figure 4.

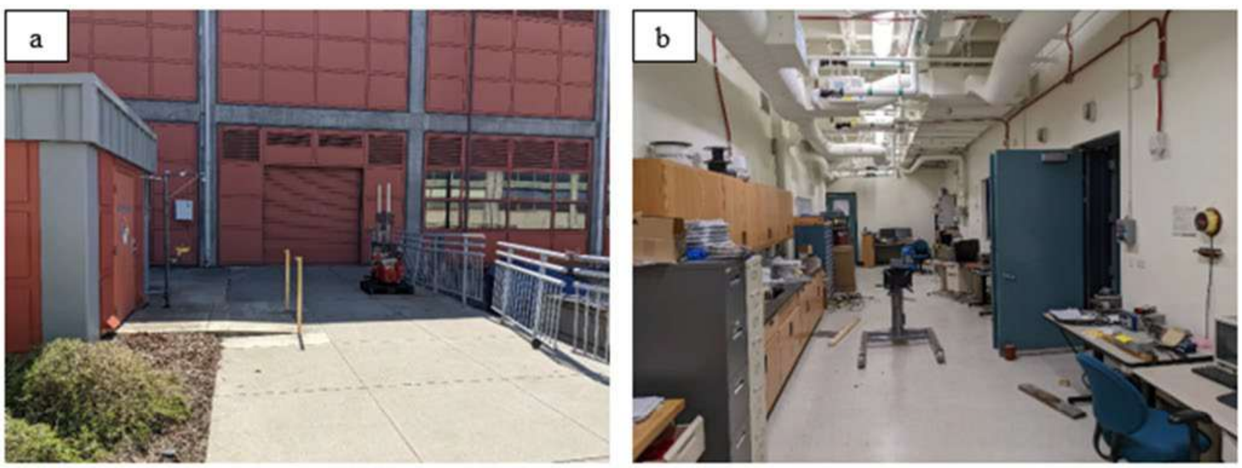

Figure 4. New Location for ElemX Inside NPS Laboratory

3.3 Machine Installation, Commissioning, and Sea Trial

3.3.1 Machine Trial at Williamsburg

A brand new ElemX machine was shipped to Williamsburg Naval Base in Virginia. The plan was to unbox and install the machine inside a Connex box and conduct a hot trial before shipping it for the underway during sea trials. Andrew Wong was trained by ADDiTEC's service team in Cary, NC, before flying back to Williamsburg to complete the installation of the new machine. Figure 5 shows the commissioning of ElemX machine in a Connex box.

3.3.2 Machine Installation on USS Essex

The next step was to commission the Connex box with ElemX on USS Essex for the underway during Rimpac 2022 (July 10 – 17, 2022). Sailing was for three weeks on the coast of Hawai and the goal was to train, operate and observe the performance of ElemX. Figure 5 shows the installation of ElemX on USS Essex. During, the following was accomplished:

- Install machine inside of hanger bay
- Train ship crew to operate machine independently
- Document environmental factors for each print while underway
- Produce NPS provided samples
- Identify and print critical components from ship
- Monitor performance at sea and ensure machine stays operational

Although the service team left on July 17th, the machine was onboard USS Essex until July 31st. The ship's maintenance officer was the primary contact and ensured the performance of ElemX was logged and reported back to technical team.

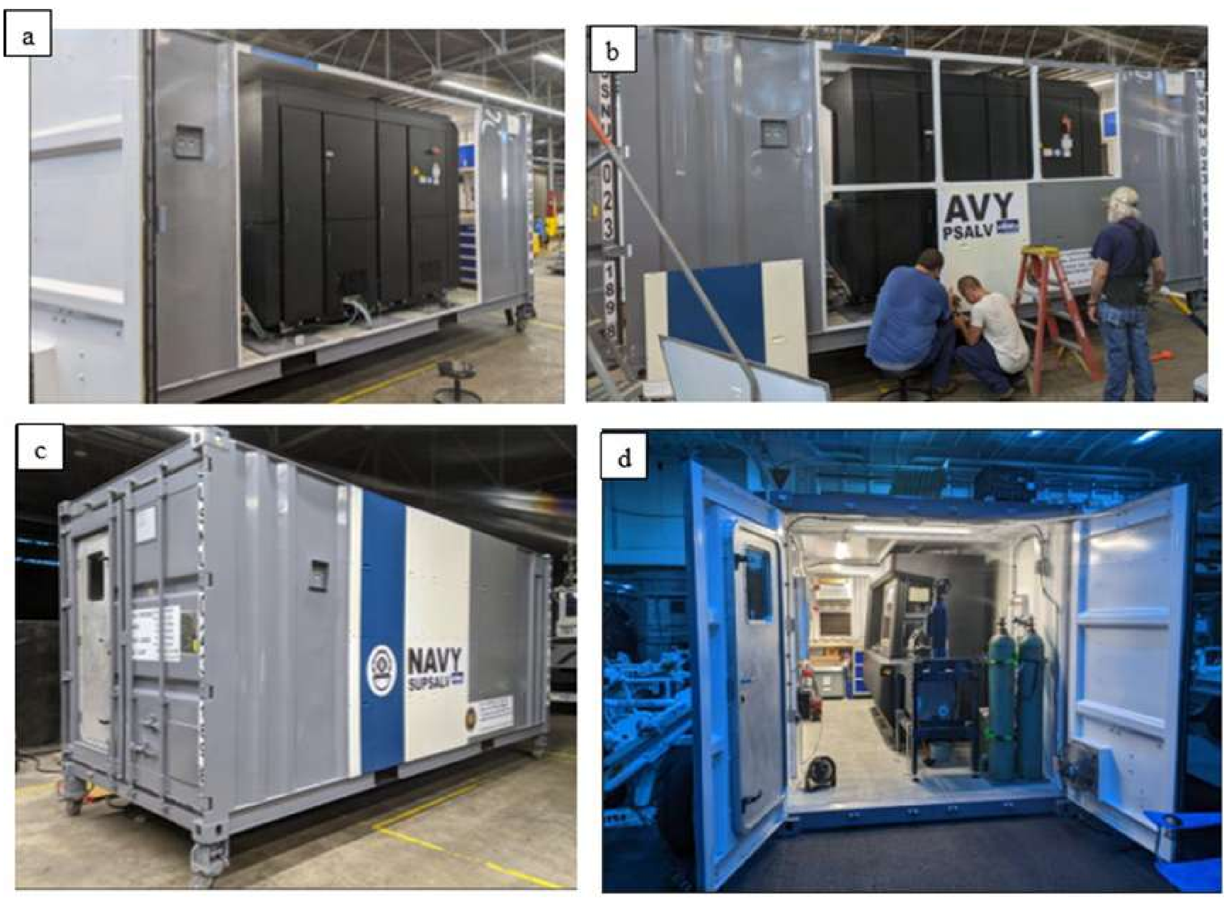

Figure 5. Commissioning of ElemX in a Connex Box on USS Essex

3.3.3 Sea Trial

ElemX went through a performance evaluation during the sea trial for three weeks from July 10 – 30, 2022. However, ADDiTEC's service team was on board until July 17th, 2022, per plan. During the period, the machine went through hot trial and sailors were trained. Predefined samples were printed onboard, as advised by NPS, as well as some critical spare parts, as advised by shipmates. Figure 6 shows ship crew getting trained onboard ship, whereas Figure 7 shows the ElemX printer in action during sailing. Figure 8 shows examples of parts that were produced during the operation.

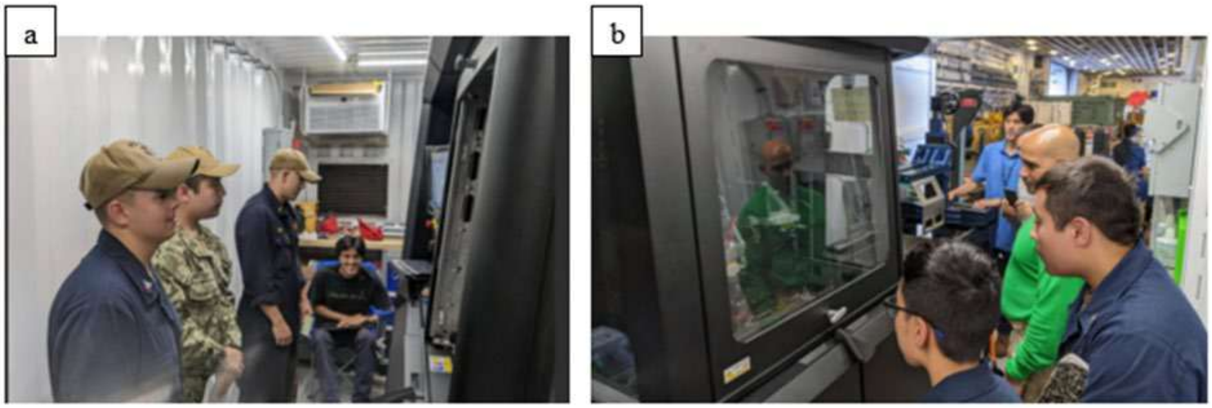

Figure 6. Ship Crew Learning ElemX Operation

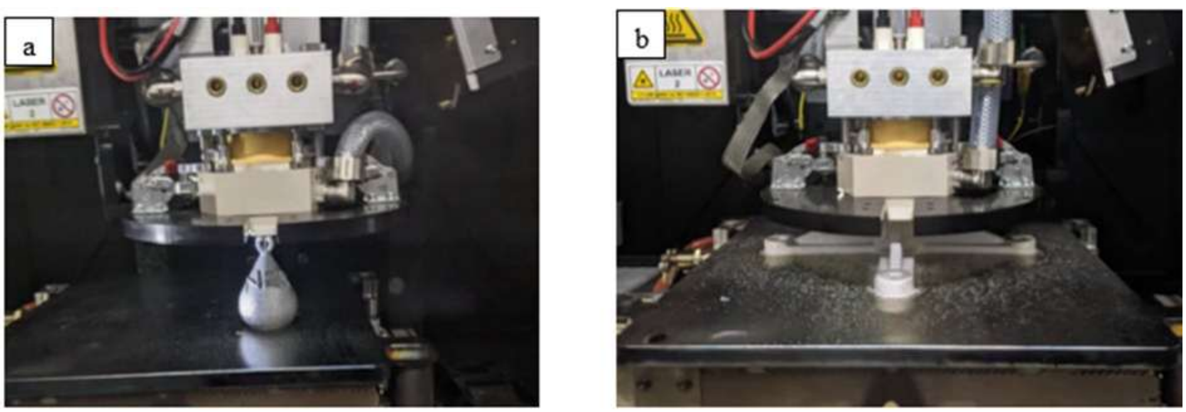

Figure 7. ElemX in Action During Sea Trials

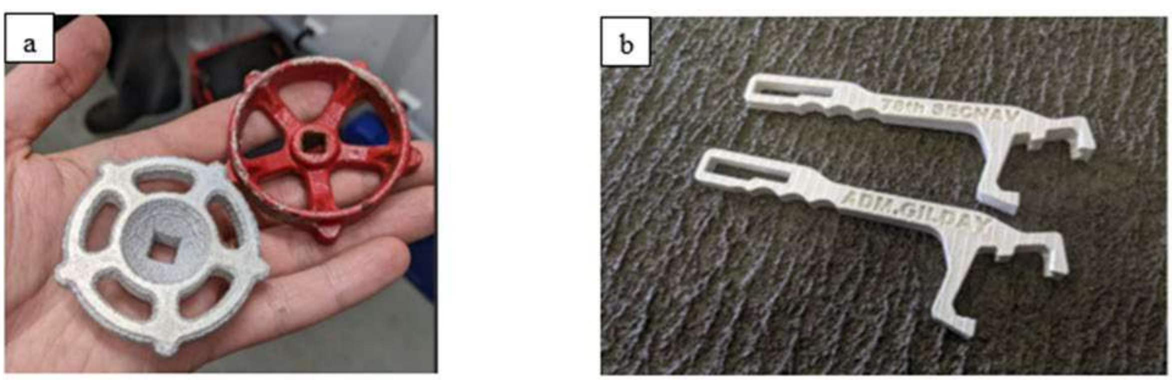

Figure 8. 4008 Aluminum Parts Printed During Sea Trials

The following observation and feedback were obtained after the sea trial:

- **Positive takeaways:**
  - Machine is capable of operating in environmental conditions of ship. No print issues observed based on ship speed, lulls, or ambient temperature.
  - Ship crew trained to operate independently within a week, while also continuing their other ship duties.
  - AT2 Waage (Sailor) performed above and beyond, presenting the machine and its capabilities to ship crew from day one. He was also able to spend significant time on the machine and showed fantastic aptitude for operation and problem diagnosis. Skilled enough to lead other trainees in machine operation by day six.
  - The crew of the USS Essex were exemplary and fully supported the project.
- **Learning opportunities:**
  - Desk scale could not be used while underway. The scale was not able to zero because of constantly changing readings. Drop mass calibration was not possible, so operation relied on rating the jetting with a visual score.
  - X-axis lead screw cover moved during transit and crashed with x carriage on first movement to build plate unload location.
  - Chiller leak detection unreliable aboard the ship. More testing is required to explain changing behavior and isolate if it is a software issue or product of the ship environment.
  - Build plate warped rapidly by day four. Measured 3.5 mm deviation from center to side of build plate. The build plate temp measured 365C when set to default of 475C on Human Machine Interface (HMI). Believed to be due to localized cooling of ladled part separation. This process is necessary to keep the water level low in dunk tank.
  - The current Connex design does not allow enough air flow to the chiller, frequently causing a constant operating temp of 27C while printer was jetting. A secondary fan or removal of an argon tank is necessary to resume 20C operation.

Each learning opportunity was evaluated, and effort was made to address by onsite repair, new development project or suggestions to Navy. Below are some actions taken to mitigate issues observed during sea trials:

- Drop mass calibration has been automated. No more desk scale is needed to measure the mass.
- Screw cover was replaced. Root cause identified was that the cover got bent during transit.
- Chiller leak detection feature was disabled for continued operation.
- Build plate warpage was due to quenching technique adopted during sailing. Sailors were pouring water around the center of the build plate instead of full quench immersion. Feedback was provided to Navy.
- Better air flow inside the Connex box will help maintaining the chiller temperature.

3.3.4 ElemX on USS Boxer and Camp Pendleton

After the underway/sea trials on USS Essex, the Navy requested to move the printer to USS Boxer in the month of October 2022. Table 1 lists service activities undertaken during the period.

Table 1. Service Tasks Undertaken on USS Boxer

Service Items	Description	Resolution
Printhead Heater Contact Terminals	Operators were observing arcing in the printhead camera. Severe pitting occurred on the printhead heater and contact terminals.	Replaced contact terminals. Examined old terminals, observed that operators were using white lithium grease on the contact terminal spring. Advised customers not to use this as a grease for this application.
Chiller Filter Disconnected Fault	Chiller front auto advancing filter became unseated, no longer contacting PCB board.	Removed filter, cleaned contacts on filter and reseated.
1319.1 Breaker Trip	During printing, visible arc was observed and 1319.1 breaker trip followed.	Inspected insulation on bed heater wires. Found small hole in insulation that allowed wires to arc to sheet metal. Replaced insulation and reset breakers.
Build Plate Clamp	The back right pneumatic clamp was not rotating without operator physically rotating when releasing the build plate. This prevented removal of the build plate.	Disassembled build plate heater module and x-carriage, replaced pneumatic clamp.

Around January 2023, the ElemX machine had to move out of USS Boxer to Camp Pendleton. Table 2 lists various issues that were serviced during that period.

Table 2. Issues Serviced During ElemX Stay in Camp Pendleton

Issues	Resolution	Status
Build plate posts severely rusted. Build plate guide pins rusted in place. Temporary fix by removing rust from posts and reassembling guide pin assembly.	New build plate posts have been created to prevent rusting issue.	Resolved
Bed heater power wire insulation burned through on front side wire causing a short to the bed heater retainer brackets. Cut out damaged section of wire and re-spliced connection	N/A	Resolved
Section of blue pneumatic line to distribution manifold has expanded, causing improper connection at push fitting, occasionally releasing from fitting. Repaired by removing deformed section back to tubing that was the proper diameter	Customer requested an electric clamping solution to remove the need for pneumatics.	Resolved
Bad jetting due to failed printhead coil. Resolved remotely with the Naval Sea Systems Command team	N/A	Resolved
Printhead unresponsive heating failure. Walked operator through troubleshooting steps. Cause of failure was broken heating element	Heating element was replaced	Resolved
Wire feed jam error. Cause was due to wire feed tubing slipping out of drive assembly. Wire bird nested inside of cabinet	Customer requested plexiglass window to view wire feed system in operation	Resolved

3.3.5 Integrated Training Exercise (ITX) 2023

ITX is a service level training exercise and the annual capstone Marine Air Ground Task Force training event for Marine Forces Reserve. ITX provides the premier live-fire combined arms training venue to assess readiness of designated units in support of Strategic Reserve Mobilization Requirements. The ElemX team was scheduled to support the ITX 2023 event in Camp Pendleton from June 12 – 16, 2023. The machine was serviced and prepared for the event. During the event several simple parts were printed (for example, different type of brackets, door handle, etc.). The goal was to evaluate various manufacturing processes under pressure and identify bottle necks, with respect to turn around time, performance of machines and quality.

3.4 Work at NPS

During the project, the following objectives were accomplished:

1. 02 ElemX Machine delivered and installed
2. Maintenance and Spares
   a. Navy
   b. NPS
3. Supplies for Printers:
   a. Spools Al 356/4008(18)
   b. Build Plate (18)
4. 03 Prototype build plate removal system
5. Enhanced training for students/sailors
6. Xerox Engineering Support – Onsite
7. Xerox Support – Remote (for software bug fixes and upgrades)

Figures 9 to 13 show the results of 6061 prints, comparison of material properties between various Aluminum alloy and hardware upgrade.

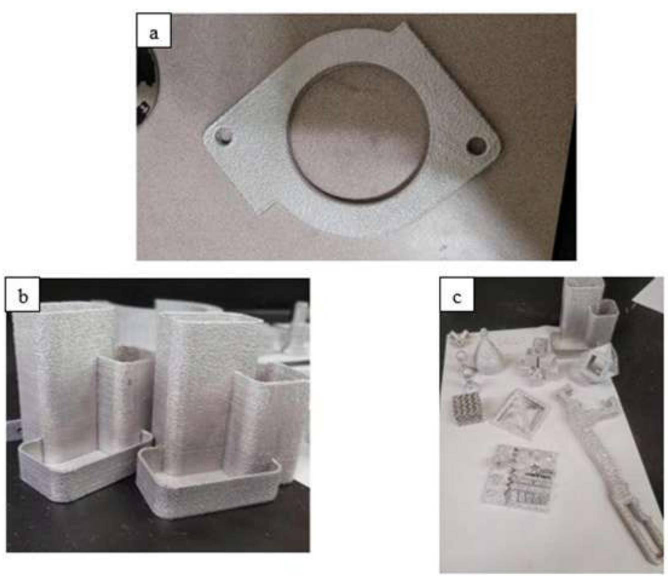

Figure 9. 6061 Aluminum Parts Printed at NPS

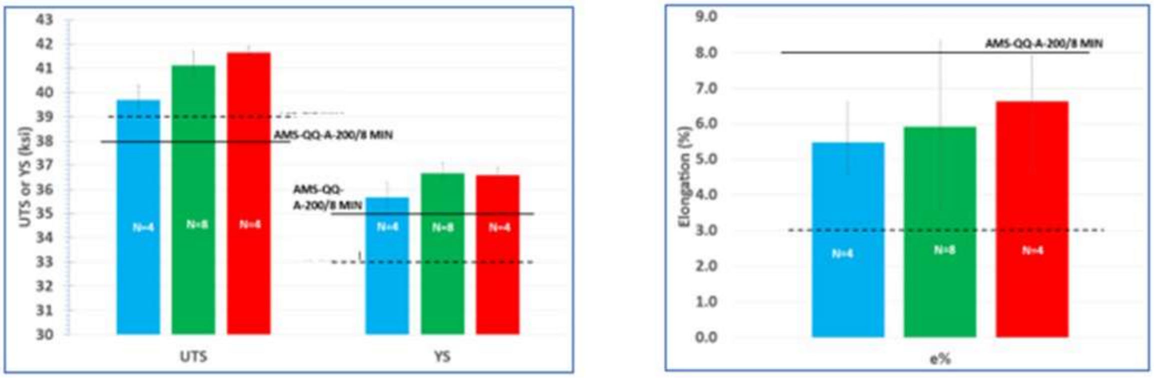

Figure 10. 6061 Material Properties in Z-Direction After Heat Treatment

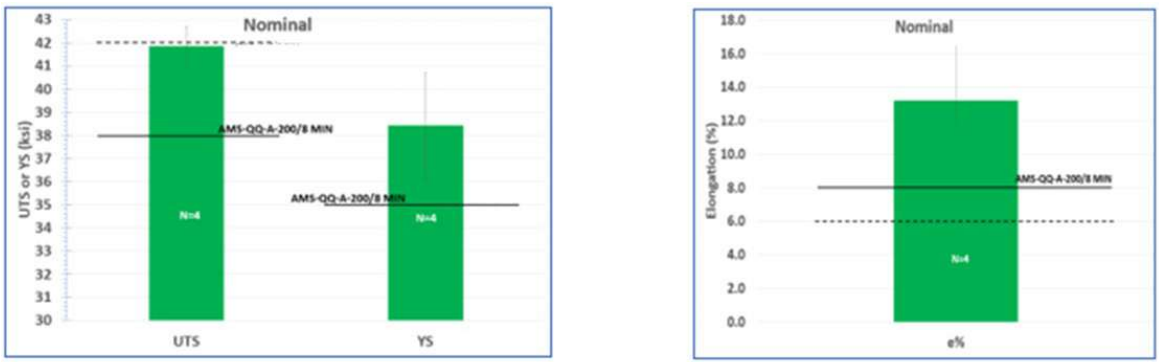

Figure 11. 6061 Material Properties in XY-Direction After Heat Treatment

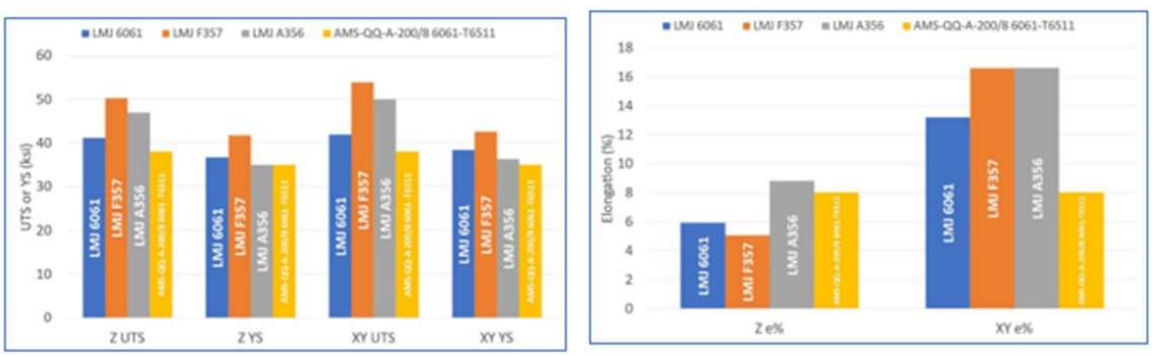

Figure 12. 6061, F357, A356 (4008) Material Properties Comparison

Figure 13. Flexure Build Plate System with 17-4PH Build Plate to Support 6061 Printing

4. Conclusions

LMJ, also known as liquid metal printing, had demonstrated capabilities which aligned with the DOD's AM strategy and ability to deploy at forward location environments both at sea and on land. The initiative focused on two principal areas of accelerating the adoption of liquid metal printing in the DON. The first is focused on enhancing the deployability of the LMJ technology; the second is focused on establishing AM education hubs to enable parts-on-demand printing for MRO applications.

This report captures various outcomes of the funded project. Chronologically it takes the reader from the beginning of the collaboration in the form of CRADA between the industry partner and NPS. Under this agreement, NPS got an opportunity to train and educate students on LMJ technology. It was also an opportunity to assess the technology from deployability perspective. Lt. Kimberl's master's thesis generated a lot of interest within the Naval community. This initial collaboration with NPS furthered the initiative by deploying a LMJ machine onboard a Navy ship.

5. Project Benefits

The project has helped in understanding and evaluating the capabilities of LMJ technology. With the current configuration it proved to be a technology that can be safely and quickly deployed and used at sea. It also proved to be the fastest to part-in-hand AM technology. ADDiTEC was able to demonstrate that it is possible to achieve cast material properties for various Aluminum alloys on the printed and heat-treated parts.

5.1 Benefits for the General Public

To meet the challenges of supply chain of critical parts, distributed manufacturing is an option which has been considered as a strategy to mitigate the risk. By having a technology like LMJ, it adds a reliable tool to the kit for manufacturing on demand capability. By meeting the objective of this project/initiative, data show that it is possible to have a technology that is easy to deploy with minimal infrastructural requirements, practically at any location (with limited modification), manufactures parts which is quicker and cheaper than contemporary technologies and much quicker to train folks with basic machine trade skills, to operate the machine. These initial advantages are critical for industrial manufacturing, to shore up supply chain resiliency and reduce the risk of loss due to disrupted supply chains.

5.2 Benefits for DOD

Any technology which can be forward deployed is an advantage for DOD. It improves the readiness of the forces and reduces the dependency on supply chain fluctuations. All the study and trials with LMJ technology point to the fact that the technology is suitable for on board, on demand manufacturing, which translates to safer (when compared to metal powder AM technologies), easier (easy to learn and operate the printer), rapid prototyping and produce direct parts (faster print to parts in hand and quicker iteration, if design changes are needed). Incorporating the successful results derived from this project allows DOD to improve readiness by increasing the overall throughput and reduce the cost of maintenance and sustainment errors, which will ultimately improve and better support the readiness of all Navy ships.