Newsletter 2017 No.2

iMAST

INSTITUTE FOR MANUFACTURING AND SUSTAINMENT TECHNOLOGIES

IN THIS ISSUE

DIRECTOR'S CORNER

Timothy D. Bair

The men and women of the Applied Research Laboratory (ARL) are very proud of the work they do to support our nation's defenders. I hope this newsletter gives you an idea of what your taxpayer's funds are supporting and that it is money well spent. This edition of the Institute for Manufacturing and Sustainment Technology (iMAST) Newsletter is a good example of how your investment continues to contribute. The institute notes are a very brief update to an article that first appeared in our second edition of the 2014 Newsletter. That article discussed the highly successful tool development project that resulted in implementing an Ultra High

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A Glimpse of Additive Manufacturing in Naval Maintenance and Sustainment

Figure 1: Boeing AV-8B Harrier II Jump Jet*

Introduction

"3D Printing" is rapidly entering the world of the sublime and commonplace. After all, it is available commercial off-the-shelf at your business supply or hardware store for less than $1000 for a good one! Additive manufacturing (AM) concepts may initially seem similar, but things can get complicated…fast. This article aims to give a glimpse into the subset of requirements needed to qualify a laser-based additive repair process for the Navy to address a fretting wear problem on existing parts that were manufactured using traditional machining methods. This project, and the AM challenge it represents, was considered "low-hanging fruit" in the realm of AM. However, its relative simplicity pales in comparison to the requirements needed to qualify a part repaired by this process much more so, one that is produced entirely via AM processes. The primary drivers motivating laser-based AM repair for the specific case at hand included: 1.) faster turnaround time (compared to part replacement/re-manufacture) and 2.) lower distortion (compared to traditional arc-based welding).

*U.S. Navy Photo Credit

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DIRECTOR'S CORNER

Pressure (UHP) tank cleaning tool set. Since that early project, ARL has been at the core of most of the Navy's innovation and safer operation of UHP tools. I highly recommend you contact us if you have questions about this technology domain.

The main article covers an area that seems to be on the verge of interest saturation, Additive Manufacturing. While we have published articles on that subject before, one aspect of it that does not seem to get a lot of attention is AM in repair. Under the ONR RepTech program, iMAST is supporting a project, in collaboration with Fleet Readiness Center – East, to explore the use of powder-fed AM in the repair of aircraft components. We think this is a natural extension of this rapidly maturing technology and are working hard to see it become a part of mainstream manufacturing and repair here at ARL/Penn State.

The main article herein covers an area that seems to be on the verge of interest saturation, Additive Manufacturing.

Before you move onto the technical articles, I would like to share some really great news relating to the staff of iMAST. First, I would like to express my thanks to Ms. Brenda Kephart for her six years of loyal and dedicated service to iMAST as our Administrator. I tell her at least once a year that I could not lead this Navy ManTech Center of Excellence without her. Thankfully, I was able to express my appreciation to her this year with a promotion. It was overdue, but nonetheless, well earned and deserved. Second, I am equally happy about the addition of Dr. Melissa (Missy) Klingenberg to our staff. Missy brings a lot of engineering project management and advanced materials expertise with her, and we are looking forward to her drive to enable our continued success and growth. Congratulations to Brenda and Missy!

As a final note, while I would like to think that ARL has the emerging technology market cornered, I welcome input and advice from readers and equally concerned patriots. ONR's ManTech program is charged with incorporating innovative technology to make new systems cheaper, more reliable, and effective. If you have ideas for projects or technologies that you think we should be considering, please contact us. Thank you for reading this edition of the iMAST newsletter, and we hope you enjoy the articles.

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A Glimpse of Additive Manufacturing in Naval Maintenance and Sustainment

Background

Who is doing it?

The Applied Research Laboratory (ARL) at The Pennsylvania State University (Penn State) is a Department of the Navy (DoN) University Affiliated Research Center (UARC), focusing scientific and engineering expertise toward many disciplines of interest to the Navy. As such, ARL/Penn State has also become a national leader in additive manufacturing, primarily of metal components using laser-based processes, operating the University's Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D). Through the Defense Advanced Research Projects Agency (DARPA) Open Manufacturing Program, CIMP-3D has been designated an AM Manufacturing Demonstration Facility for the DoD.

Additive manufacturing projects conducted at CIMP-3D and sponsored via the Office of Naval Research (ONR) Manufacturing Technology (ManTech) and Repair Technology (RepTech) programs, through ARL/Penn State's Institute for Manufacturing and Sustainment Technologies (iMAST), a U.S. Navy ManTech Center of Excellence (COE), have resulted in extensive research and development toward the design, qualification, and implementation of parts manufactured entirely via AM processes as well as toward parts manufactured primarily via traditional, subtractive means and then modified via additive processes. The project described here directly supports the Naval Air Systems Command (NAVAIR), as the anticipated culmination will be the implementation of AM-based repairs at the respective NAVAIR repair depot, Fleet Readiness Center (FRC) East.

Additive manufacturing is getting a lot of attention. It offers a new means to build "things" from the ground up, piece by piece, as one might build a toy with Lego building blocks.

Figure 2: Lego plane (Compare to a small, low-resolution AM build)

What is AM?

Simply put

Additive manufacturing is getting a lot of attention. It offers a new means to build "things" from the ground up, piece by piece, as one might build a toy with Lego building blocks (see *Figure 2*). The completed things/builds can be single parts or multiple parts. Consider, e.g., that the interconnected links of a chain could be additively manufactured all at once as a functionally complete system. For simplicity, however, we will also refer to the output of a single, independent AM process grammatically as a singular "build" (or "part").

Underlying complexity

As the number of pieces/"building blocks" increases and the size of the building blocks compared to the size of "the build" decreases, the potential respective resolution becomes increasingly high, as does the potential number of ways to achieve the same resulting geometry (see *Figure 3*)—not to suggest that geometry is the only driving factor. This offers a myriad of opportunities to the AM engineer, made possible ("if" possible) previously only via very complex "assemblies". Note that quotes are used here only to emphasize that AM builds are typically not discussed as being "assemblies" (like a Lego set, which could also be disassembled). But they are being discussed using the terminology of "parts", or more formally as "builds",

Figure 3: Jim McDonough's Lego USS Missouri (Compare to larger, higher-resolution AM build)

as they are generally represented by completely fused together "pieces". Moreover—keeping with the Lego analogy a bit longer—just as different Lego building blocks (e.g., "colors") may be interconnected because of their common structure to form a single "build", the realm of AM similarly offers countless options of incorporating different materials into a single build, whether plastics, metals, or others.

Clearly, the potential with AM is high, but this complexity comes at a cost. If the "Lego building blocks" do not overlap well, the completed assembly will be weaker, even if it looks the same from the outside. So, too, the AM engineer, even given a single-material build, must consider many variables—many of which are not fully understood and/or controlled sufficiently by the current state of the technology to predict the ultimate outcome. The solution for critical builds thus often entails an iterative learning process with a lot of testing and analyses to strengthen confidence in a single part/build design and build process before it (they) may be qualified for use.

There are many ways to skin a cat, but not all are equal. So, the product is married to the process. And the AM "build" definition/documentation must therefore include—not only simply mechanical drawings with geometry and bulk material specifications—but also the processing parameters necessary to repeat the build (and/or sufficient information to define the desired nature of the part), which can be extensive. After all, a child could re-create the Lego airplane shown in *Figure 2* using that figure alone, but Mr. McDonough's ship shown in *Figure 3* would require an extensive manual of step-by-step instructions. Additively manufactured builds may occupy a smaller footprint than this ship, but their respective resolution, complexity, and necessary manufacturing documentation (hardcopy and/or digital) could "outweigh it".

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Project Objective and Goals

Project background

Production of Boeing AV-8B Harrier II (see *Figure 1*) aircraft began in 1981 and continued to 2003. The U.S. Marine Corps will continue flying them through 2025, or until they are replaced by F-35B's. During these post-production years, parts inventories are naturally lower, and the turnaround time to repair/replace components can increase, at the cost of asset availability and fleet readiness.

A Navy ManTech (RepTech) project was initiated to develop and demonstrate AM repair qualification and certification procedures on a targeted, high-priority component: the AV-8B's F402 engine Low Pressure Compressor (LPC) 2nd Stage Rear Seal Ring (see *Figure 4*). During operation, these non-rotating titanium components experience fretting wear at pinned (not bolted) contact points to their mating LPC 3rd Stage Front Seal Rings, via the slight movement/vibration of stainless steel packing washers on the same pins. Engine service specifications require the repair/replacement of parts exhibiting such fretting wear. However, for the case at hand, no repair option (though attempted via arc-based welding) had been previously qualified. And, when/if inventories diminish, the manufacture of new parts (limited to the OEM) can lead to undesirable delays in asset availability.

Specific goals

ARL engineers were able to very quickly (within a week or so) produce a pretty good additive repair to a seal ring sample provided at the outset of this project using a laser-based, powder-blown AM process. The primary technical goal of the project, however, was to develop a suitable repair process for the noted part, which also included:

- Generating, vetting, and finalizing a qualification test plan (QTP),
- Developing an optimized AM repair process that met the qualification standards,
- Generating and testing coupons and full scale test articles per the accepted QTP, and
- Composing a technical data package (TDP) to enable the transfer of the process to FRC East.

As such, the ensuing two years were invested in documenting, proving, and qualifying the repair/process for implementation at FRC East.

Figure 4: Cutaway view of F402 engine, with CAD representation of the LPC 2nd stage rear seal ring, designating its location within the engine, along with the sites (green ellipses) of typical fretting wear

Obstacles Overcome

Limited "standards" for AM

Stemming from prior ARL/Penn State work with the Naval Sea Systems Command (NAVSEA) that implemented AM repairs on submarines, early drafts of the QTP were based on NAVSEA welding standards (cf. MIL-STD-248) written before AM technologies were familiar to industry. As such, specific testing "requirements" were not found for an AM weld repair on which to base the QTP. Therefore, the project team proposed a series of tests (not all of which were retained in the final, certified QTP document) based on prior experience with AM repairs in general and with specific knowledge of attempted repairs using arc-based processes to these seal rings.

An initial, thorough round of testing followed, that produced insights into the value of the tests initially proposed. This initial testing also showed the need for a second round of testing. Ultimately, a more applicable aerospace standard (cf. AWS D17.1) was found that helped the qualification process by offering guidance and test metrics for "some" of the tests included in the QTP. The final tests and metrics required for qualification are summarized in *Table 1*, wherein small, representative test coupons were used for all of the tests, except for Overall Distortion testing, which required the repair of a full-scale seal ring.

Insufficient "best practices"

Producing and analyzing test coupons, per a proposed design of experiments, in order to define, document, and prove/qualify the repeatable output from a given set of input parameters is one part of implementing a relatively new technology. Another (completely dependent) part is knowing and controlling the input parameters. For example, OEMs of AM machines typically offer suggestions and/or "best practices" to get improved results. These are usually only a very small subset of the many potential parameters available in the execution of an AM build. When such are provided, it can be easy to assume that significant sources of directly related output variability will be controlled if the "best practices" are followed.

Table 1: Qualification Test Plan tests and metrics

Test Type	Test	Metric (simplified for clarity)
Non-destructive	X-Ray (CT)	No spherical voids greater than 0.007"
	Liquid Penetrant	No observable defects
	Overall Distortion	Tolerances within 50% from "as-received" condition
Destructive	Guided Bend	No spallation defects/cracking
	Macro-Etch	Buildup discontinuities ≤ 0.007"

During the initial phases of this project work, an independent project at ARL funded by the Air Force to produce AM repairs on titanium showed the fallibility of one such assumption related to the flow of powdered metal into the melt pool created by the laser. Project engineers developed a novel means to measure and characterize this powder flow. Following months of unanticipated (at the project outset) work specifically related to the characterization and ultimate control of this flow of powdered metal, the results of these analyses (with subsequent and necessary benefit to the repeatability of the resultant AM depositions) will be included in the primary final project deliverable (the TDP) required to fully transition the technology to FRC East.

Conclusions

The project team has been able to successfully define, document, and qualify processing parameters able to sufficiently repair areas of fretting wear on F402 engine seal rings that had no prior history of successfully qualified repairs. Images showing some of the steps in this process are shown in *Figure 5*. Moreover, given the recognized value of this technology, being further proved following the initial set of QTP testing specific to the noted high priority need, FRC East is currently seeking approval for a capital investment project (CIP) to procure AM equipment.

This project will end following the transfer to ONR and FRC East of final documentation including the TDP and final project report in September 2017. A potential follow-on ManTech project is now being developed to further apply the same AM technologies to the repair of several nickel-based parts on the T64 engine. These parts suffer similar issues of excessive distortion, following attempts at arc-based weld repairs. A ManTech project to qualify their repair thus offers the potential to yet further realize and expand the benefits of laser-based AM repairs for NAVAIR, in addition to increasing the return on investment (ROI) as a result of this ONR (ManTech) and FRC East (CIP) funding investments.

Stephen W. Brown has over 15 years of professional engineering experience, 10 of which he served the U.S. Navy and industrial sponsors through the Laser Systems Engineering and Integration Department at ARL/Penn State. His areas of expertise extend from mechanical and engineering mechanics background to the integration of electrical, optical, and software aspects of laser-based systems. For the past 5 years, his primary focus has been on additive processes in metals. He designed and built a complete multi-kilowatt directed energy deposition system in use at the ARL's Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D) and has led other projects culminating, for example, in a cladding system deployed at Pearl Harbor Naval Shipyard to repair pitting and corrosion damage within Vertical Launch System (VLS) missile tubes on Los Angeles Class submarines.

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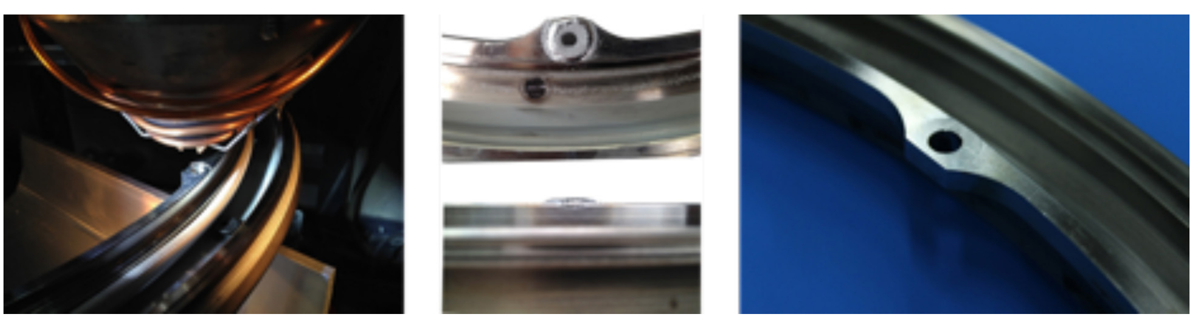

Figure 5: Seal ring repair site before (Left) and after (Middle) deposition, and after final machining (Right)

iMAST UHP WATERJET TECHNOLOGY DEVELOPMENT EFFORT UPDATE

Since the 2014 article on ARL's ultrahigh pressure waterjet (UHPWJ) technology, iMAST has supported further development of UHPWJ tools for all four Navy shipyards. Below is a brief overview of three new developments in UHP: a semi-automatic dual track UHPWJ system, an epi-cyclic waterjet system, and high pressure/ high volume waterjet cleaning tools.

The semi-automated dual-track UHPWJ system (see *Figure 6*) was designed, fabricated, and demonstrated by ARL to remove submarine hull treatment coatings. It was recently repurposed by Naval Surface Warfare Center Carderock (NSWCCD) to perform required sensor health assessments and hull condition inspections, as well as enabled large-scale removal for vertical stave section replacement, inspections, and maintenance needs. Finally, the Dual Track system successfully demonstrated its flexibility as a platform for a three-axis automated router system. Improvements planned include proximity switches for safety control, better computer control of all three axes, better hull mounting approaches, optimized handling fixtures, and integrated waste collection.

The epi-cyclic waterjet nonskid removal devices enable shipyard transition from time-consuming sanders or disc-grinders (e.g., 6ft^2/hour removal rate) to high removal rates (e.g., 35, 90, and 135 ft^2/hour, respectively) for Dura X, Dura 1, and Versathane non-skid coatings. Even higher removal rates (i.e., 55 to 200 ft^2/hour) are possible in unencumbered areas. Four units are being built by ARL for delivery to Navy shipyards in December 2017.

Lastly, four modular, portable, HPHV (≤20 ksi and ≤20 gpm) waterjet cleaning tools were delivered to the Navy shipyards by ARL. These systems, complete with a rotating, dual-jet nozzle holder mounted on a rotating cylindrical body, enable shipyard personnel to easily move it into and around small, complex tanks to reduce cleaning time by 50% and enable complete removal of all organic contaminants. Removal of contaminants enables tanks to be painted, thereby reducing corrosion and saving an estimated $28M over the remaining life of the 688 Class (for NFO tanks only).

These successful efforts support PMS 392, PMS 450, and other Navy organizations in reducing cost and improving safety in Navy submarine maintenance and repair operations.

These systems also can be used as the basis for the development of additional, robust systems that can be used for similar removal applications in the shipyard environment.

These systems also can be used as the basis for the development of additional robust systems that can be used for similar removal applications in the shipyard environment. Work continues at the shipyards to expand the applications of these systems.

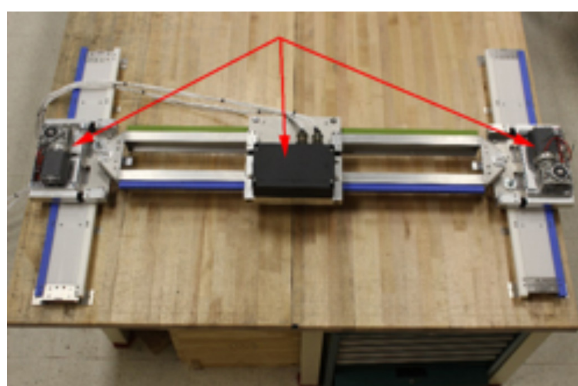

Figure 6: Prototype semi-automated dual-track UHPWJ system

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There's no shortage of good ideas, I'll say that, so where I'm trying to focus is the much less exciting process development, so that when you have a genius idea, what's the quickest way to make that thing real?

— Admiral John Richardson USN, Chief of Naval Operations

CALENDAR OF EVENTS 2017/2018

4 – 7 December	**Defense Manufacturing Conference**	****Tampa, FL**
4 – 7 December	**DoD Maintenance Symposium**	**Salt Lake City, UT**
9 – 11 January	**Surface Navy Association**	**Crystal City, VA**
13 – 15 February	**ASNE Day**	**Washington, D.C.**
27 – 28 March	**ShipTech**	****Charleston, SC**
9 – 11 April	**Sea-Air-Space 2018**	**National Harbor, MD**
22 – 25 April	**GEOINT**	**Tampa, FL**
22 – 24 May	**Mega Rust**	**San Diego, CA**
30 May – 1 June	**Showcase for Commerce**	**Johnstown, PA**
17 – 20 September	**Fleet Maintenance & Modernization Symposium**	****Virginia Beach, VA**
25 – 27 September	**Modern Day Marine Expo**	**Quantico, VA**
	DoD Maintenance Symposium	**TBD**
	Defense Manufacturing Conference 2018	****TBD**

**** Please stop and visit the iMAST booth**