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14. ABSTRACT Metal additive manufacturing (AM) has significant relevance to the missions of all branches of the Department of Defense (DoD) as it has the capability to bring parts to the warfighter more quickly and cost effectively However, DoD's goals of utilizing and deploying AM will not be achieved without substantial research and development to address the technology's current limitations, which exist at every facet of the AM value chain. The DURIP award, along with supplementary funding provided by Virginia Tech, enabled the acquisition of a reactive metal laser powder bed fusion (LPBF) AM system. The advanced AM system acquired through this program features open-access to all process parameters and features integrated in-situ monitoring technologies that enable research focused in increasing materials selection, creating new design for AM tools and methods, enhancing part quality through process-property-structure models, in-situ monitoring and post-processing techniques, and securing the platforms from cyber-physical vulnerabilities. The system is installed as a showcase piece in a newly created multidisciplinary educational and research space dedicated to preparing undergraduate and graduate students for future careers in Industry 4.0 technologies. As such, the new system will enable multi-disciplinary research and education across the entire value chain of AM.

15. SUBJECT TERMS
Additive Manufacturing, 3D printing, powder bed fusion, cyber-physical security, thermoelectric, Industry 4.0

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ACQUISITION OF A LASER POWDER BED FUSION SYSTEM TO TRANSFORM THE ADDITIVE MANUFACTURING VALUE CHAIN

FINAL PERFORMANCE REPORT

Expeditionary Maneuver Warfare & Combating Terrorism S&T

Department Code 30 Logistics

Thrust Area Program Manager: Dr. Billy Short

PI: Dr. Christopher Williams; L. S. Randolph Professor, Department of Mechanical Engineering, Virginia Tech

1. INTRODUCTION

Through the DURIP award, Virginia Tech's multi-disciplinary Manufacturing Team acquired a laser powder bed fusion (LPBF) additive manufacturing (AM) system capable of processing reactive metals. The aim of the acquisition was to enable research and education across the entire value chain of AM, with specific focus in programs related to advancing (i) LPBF-processable materials, (ii) new "design for AM" tools and methods, (iii) multiscale models of process-property-structure relationships, (iv) in-situ monitoring and post-processing techniques for improving AM part quality, and (v) security from AM process cyber-physical vulnerabilities.

Selection of a laser powder bed fusion additive manufacturing (LPBF-AM) system was guided by key process requirements that would enable the team to accomplish their research objectives. These requirements include:

i. the ability to process reactive materials,
ii. open-architecture system configuration that allows for modification of process parameters for materials and process research,
iii. opportunity to reduce build volume so as not to consume significant amounts of experimental materials,
iv. and offering of integrated, in-situ sensing to enable process monitoring for process optimization, quality assurance, and cyber-physical security research,

To meet these requirements, the team acquired a SLM Solutions SLM 280 2.0 LPBF-AM system (see Section 2 "Equipment Details"). Acquisition of this larger, more capable system was accomplished thanks to Virginia Tech's additional financial supplements ($335,000) to the original DURIP award.

The system was delivered to Virginia Tech on March 20, 2020 – three days following a campus closure due to the COVID-19 pandemic. Unfortunately, progress on necessary facilities renovations and system installation were delayed due to the COVID-19 pandemic (see Section 3 "Special Circumstances Surrounding any Change from the Grantee's Proposal"). Facility renovations and system installation are currently estimated to be completed by May 2021 (see Section 4 "Discussion").

2. EQUIPMENT DETAILS

- *Type of Equipment:*
  - Metal Powder Bed Fusion Additive Manufacturing
- *Manufacturer of Equipment and Model Number*:
  - SLM Solutions SLM 280 2.0
- *Cost of Equipment:*
  - $600,000

Figure 1. SLM 280 2.0 LPBF System

- *Quantity*:
    - Base Machine SLM 280 2.0: Single laser 400W Tank Feed
    - Install Bundle – Full: SLM 280 2.0 (1 year warranty, installation, training, etc.)
    - PSM100 Stand Alone Powder Sieving Station
    - Laser and Melt Pool Monitoring
    - RUWAC Vacuum cleaner MX361
    - Powder Flow Meter
    - Powder Moisture Measuring Device
    - SLM 280 Build Volume Reduction (BV100) 100x100x170mm
    - Magics SG+ Module Fixed License
    - Magics SLM Build Processor Fixed License

3. Special Circumstances Surrounding any Change from the Grantee's Proposal

The original proposal, and subsequent award, was for an amount of $265,000. In the original proposal, the PIs identified the Concept Laser's Mlab Cusing R system as a potential fit to meet the machine requirements listed in Section 1 while also meeting the budget constraints. However, following careful review, it became clear that, while the Mlab Cusing R system provided open access to altering some process parameters and provided the ability to process reactive metals, it did not feature sufficient embedded in-situ process monitoring options, and had a small build volume (90x90x80 mm), which would prevent the PIs from accomplishing some of their research goals.

In an effort to acquire a more capable LPBF-AM system that could meet all PIs' requirements and could provide the greatest research impact, PI Williams worked with Virginia Tech administration to identify a post-award cost-share to supplement the award amount. While these negotiations slightly delayed the purchase of the system following the receipt of the DURIP award, they led to an additional $335,000 in support from the university (across two different administrative offices and two academic departments) to support the purchase of a metal LPBF-AM system that best fit the needs of the research team and the aims of the proposal. Simultaneously, Williams worked with SLM Solutions, LLC to identify a competitive purchasing price which leveraged academic discounts and enabled the purchase of a larger LBF-AM system that would fit the newly expanded budget.

As a result of this effort in augmenting the original DURIP award amount, the Virginia Tech team was able to acquire the SLM 280 2.0 system, which met the researchers' identified system requirements:

i. *Reactive materials:* The SLM 280 is able to process non-reactive and reactive metal powders. It features a novel process for filter exchange that keeps the metal condensate under inert atmosphere throughout the process to ensure the safety of the operators.

ii. *Open-architecture system configuration*: The SLM 280 provides users access to alter all process parameters at no additional/annual cost. Through integration with commercial software (e.g., Autodesk netfabb) users can alter and simulate unique toolpath strategies. This capability provides the team the opportunity to explore novel materials, unique process parameters and toolpath strategies, and process-structure-property relationships.

iii. *Build volume reduction*: The included powder bed reducer, which reduces the build envelope to 100x100x170 mm, allows for evaluation of small quantities of novel (and/or expensive) powders.

iv. *Integrated, in-situ process monitoring*: Virginia Tech's purchased SLM 280 system includes both the integrated laser power monitoring (LPM) and melt pool monitoring (MPM) capabilities. Using a series of beam splitters and photodiodes, the LPM takes measurements of the laser power provided throughout the build at a rate of 100 kHz; the data is provided with a uniquely assigned time stamp and transmitted to PC via LAN. The MPM system leverages the fact that radiation from the exposure of welded powder particles is a thermal signal which is diffusively emitted from the melt pool. A series of beam splitters and two photodiodes deflect the melt pool's emitted thermal signatures along the optical axis and in the opposite direction of the laser beam to the monitoring system. The measurements of melt pool temperature are provided in x/y coordinates every 10 μs. All measurements of each layer are stored in a unique data file with timestamps; each file is a 2D representation of the whole build platform and the associated thermal signatures. These process monitoring functionalities is critical for the research team's research activities in process optimization, quality assurance, and cyber-physical security research.

The negotiations with the Virginia Tech administration and SLM Solutions took several months. The system was purchased on December 2019 and was delivered on March 20, 2020. The COVID-19 pandemic caused the Virginia Tech campus to close for several months (starting on March 16, 2020), which significantly delayed the facilities improvements required to complete the installation of the LPBF-AM system. In addition to upgrades in voltage/current delivery to the room, additional HVAC ducting was needed to evacuate argon gas from the room in the event of an emergency. The machine's ability to process reactive metal powders also required additional checks, procedures, and policies in accordance to Virginia Tech's Environmental Health and Safety office and the local fire codes. The continued pandemic and the associated constraints imposed on personnel and facilities work have further delayed the installation of the system. Fortunately, the facility upgrades and system installation will be completed by May 2021.

4. Discussion

Unfortunately, due to the COVID-19 -induced delays in system installation, the researchers have not yet had the opportunity to use the newly acquired LPBF-AM system in their research work. It is anticipated that the system will be installed in May 2021 where it will be immediately used on projects proposed in the original DURIP proposal including:

- *AM Cyber-physical security*: PIs Williams and Kong will explore the SLM 280s integrated in-situ process monitoring as possible side-channel measurement streams for validation of their cyber physical hash technique for passing quality control data to air-gapped manufacturing systems. In addition, the ability to directly write toolpath to SLM systems will enable the team to explore their next idea in which process quality information is communicated to the air-gapped machine through modulation of beam speed.

- *Metal-matrix graphene composites*: PI Mirzaeifar will experimentally explore processing of metal and graphene composite powders to validate his modeling efforts. The outcome will be fabrication of metallic parts with complex geometries and exceptional mechanical properties.
- *In-situ process quality assurance*: PI Kong will use the system to fabricate specimens to support his ONR MURI research which aims to correlate and characterize the relationship among (i) process Parameter, which are AM machining parameters setting and material specifications, and usually considered as system input; (ii) process State, which reflects the dynamic characteristics of the material being printed,; and (iii) product Quality, which is considered as system output, with geometrical, mechanical, and physical aspects. He will use the LPBF-AM system to make specimens for x-ray CT and structured light scanning, which will be used for verification and validation of existing integrated computational materials engineering models for AM processes.
- *LPBF-AM of thermoelectric materials*: PI Zuo will explore printing of thermoelectric materials to enable re-imagining of solid-state thermoelectric generator devices for energy harvesting applications.
- *Hot-isostatic pressing of LPBF-AM parts*: PI Tallon will explore the impact of HIP post-processing parameters on the final properties of LPBF parts including (i) residual porosity and (ii) presence of flaws and residual stresses from layering.
- *Additive Manufacturing workforce development*: The system will be integrated into PI Williams's and Co-PI Yu's Fall 2021 courses related to Additive Manufacturing processes, advanced metal processing, and design for AM methods. In addition, the machine's capabilities will be made available to senior-level student project design teams.

Virginia Tech's additional contribution to the base DURIP award amount enabled the purchase of a SLM 280 system that meets the desired specifications outlined in the original proposal. The system features a larger build volume and integrated process monitoring capabilities that will allow the team to meet all of their research goals.

Upon the submission of the DURIP proposal, the team had identified a small laboratory room to house the metal LPBF system. However, following the selection of the larger SLM 280 system, and additional clarity on the requirements of facilities housing reactive metal LPBF systems, a different lab space was selected for its installation. The SLM 280 system will be installed within Virginia Tech's Institute for Critical Technology and Applied Science (ICTAS) in Kelly Hall. Specifically, it will serve as a showcase instrument in ICTAS's new "Industry 4.0 Lab", which is a dedicated, integrated research and educational space for technologies related to the next-generation 'smart factory' enabled by automation and data exchange among manufacturing systems. This shared research lab will provide open access to a broad base of university researchers across the university. It will also be a focal point for several new undergraduate educational programs focused in advanced manufacturing. For example, students in Virginia Tech's Calhoun Discovery Program – an interdisciplinary Honors program focused in experiential learning around Industry 4.0 themes (and funded through partnerships with Boeing, Catepillar, and GE) – will conduct their research projects in this new laboratory.

The new Industry 4.0 lab provides sufficient space to house the SLM 280 system, its auxiliary equipment, and other advanced manufacturing technologies. One area of opportunity is in the integration of co-bots to explore automation and industrialization of LPBF-AM systems. For example, student projects will focus on using these systems to automate inspection, part tracking, cleaning and post-processing of printed parts, and filter exchanges.

Before installation of the SLM system, the lab space had to be renovated to accommodate the printer's unique facilities needs. These renovations included installation of high voltage power, installation of water spigot near the system for powder filter inerting, gas canister wall braces, and installation of new HVAC ducting to exhaust the machine's inerting gas. A blue print of the laboratory space is shown in Figure 2, which illustrates the required changes including new wall installation (green dashed line), demolition of wall components (purple cloud), and SLM 280 system footprint (red dashed lines). A picture of the room is provided in Figure 3, which includes photos of the SLM system crates awaiting unloading and installation.

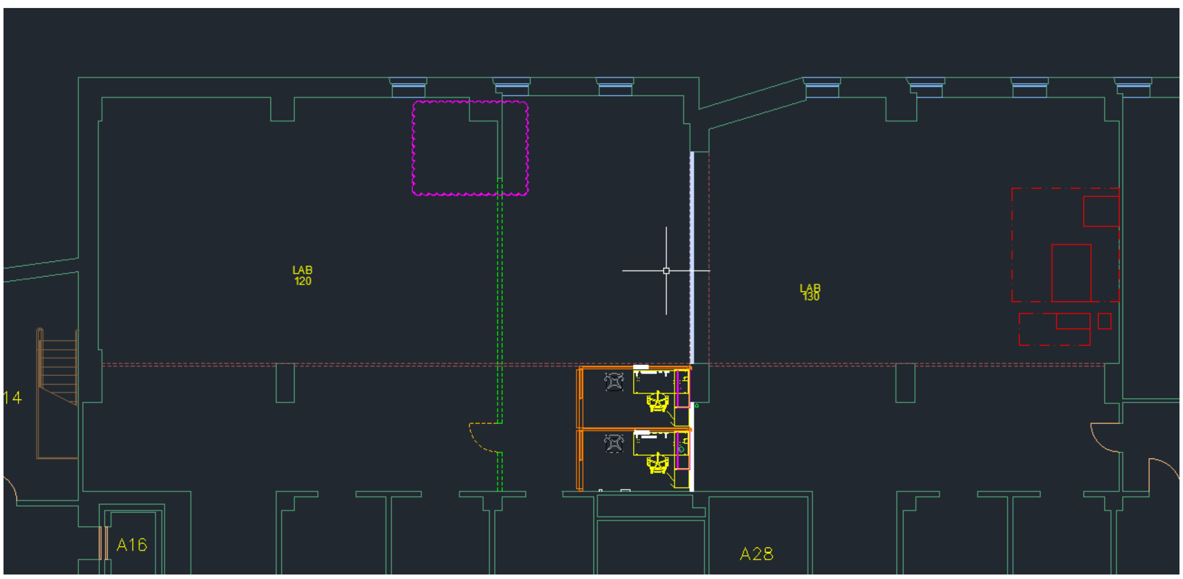

Figure 2. Blue print of renovations of the new Industry 4.0 lab

Figure 3. Picture of SLM system crates in the new Industry 4.0 lab awaiting unloading and installation