

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) 10-05-2023		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 26-Apr-2021 - 31-Dec-2022	
4. TITLE AND SUBTITLE Final Report: Extending Advanced Manufacturing Post-processing Activities through Acquisition of an Additive Manufacturing System Suite			5a. CONTRACT NUMBER W911NF-21-1-0209		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 060122		
6. AUTHORS			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Howard University 2400 6th Street NorthWest Washington, DC 20005 -9000			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 78201-SM-REP.1		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Grant Warner
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 202-806-6607

RPPR Final Report

as of 11-May-2023

Agency Code: 21XD

Proposal Number: 78201SMREP

Agreement Number: W911NF-21-1-0209

INVESTIGATOR(S):

Name: Grant Warner
Email: g_warner@howard.edu
Phone Number: 2028066607
Principal: Y

Name: Gbadebo Owolabi
Email: gbadebo.owolabi@howard.edu
Phone Number: 2028066565
Principal: N

Organization: **Howard University**

Address: 2400 6th Street NorthWest, Washington, DC 200059000

Country: USA

DUNS Number: 056282296

EIN: 530204707

Report Date: 31-Mar-2023

Date Received: 10-May-2023

Final Report for Period Beginning 26-Apr-2021 and Ending 31-Dec-2022

Title: Extending Advanced Manufacturing Post-processing Activities through Acquisition of an Additive Manufacturing System Suite

Begin Performance Period: 26-Apr-2021

End Performance Period: 31-Dec-2022

Report Term: 0-Other

Submitted By: Gbadebo Owolabi

Email: gbadebo.owolabi@howard.edu

Phone: (202) 806-6565

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 2

STEM Participants: 1

Major Goals: In April 2021, A DOD HBCU/MSI grant of \$596,000 was awarded to Howard University (HU) for the acquisition of a 3D metal printer and a Fortus 450mc Fused Deposition Modeling printer, to support an ongoing research and pipeline development project in additive manufacturing. The two machines are viewed as a well-integrated equipment set. The printing systems are research focused, production quality machines that allow for the adjustment of production parameters. The equipment is expected to accelerate progress in several active research projects and impact the education and training of several students at HU.

The equipment along with their accessories will be used to support existing and future projects including the PI's research on "Additive Manufacturing Post Processing Partnership AMP3" funded by Department of Energy. The principal goal of the project is to solidify a sustainable pipeline of under-represented students pursuing Science, Technology, Engineering, and Mathematics (STEM) degrees from Minority Serving Institutes to the National Nuclear Security Agency (NNSA) National Labs and Plants. The AMP3 consortium is the result of productive interaction among HBCUs and DOE-NNSA laboratory and industries occurred during 2013-2019. The equipment will also be leveraged to support research in materials characterization, process parameter optimization, and smart materials with embedded sensors. These are areas of ongoing research, associated with the consortium at Howard University.

The research equipment will facilitate valuable and extensive training of graduate and undergraduate students as well as postdoctoral fellows with broad based knowledge and skills in the area of additive manufacturing so that well-qualified minority graduates can enter the workforce or continue to advance research in areas that are of interest to DoD.

Accomplishments: Both the metal and plastic printers were purchased from Amtek Company, Inc. and delivered to Howard University in January 2023. Full installation was done on April 13 and 14, 2023 for the Fortus 450mc polymer printer. Full installation would be done for the metal printer as soon as the necessary fittings and gas tank are installed in the room containing both machines.

RPPR Final Report

as of 11-May-2023

Training Opportunities: Both graduate and undergraduate students working on the AMP3 projects were trained on how to use the equipment.

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Not applicable

PARTICIPANTS:

Participant Type: PD/PI

Participant: Grant Warner

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Co PD/PI

Participant: Gbadebo Owolabi

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Melody Chepkoech

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

Partners

RPPR Final Report
as of 11-May-2023

I certify that the information in the report is complete and accurate:

Signature: Gbadebo Owolabi

Signature Date: 5/10/23 4:17PM

FINAL REPORT

DOD HBCU/MSI Equipment Award Title: Extending Advanced Manufacturing Post-Processing Activities through Acquisition of an Additive Manufacturing System Suite

Award #: W911NF-21-1-0209

Application #: 78201-RT-REP

Reporting Period: April 2021-December 2022

Principal Investigator: Grant Warner

Co-PI: G. M. Owolabi

Institution: Howard University, Washington D.C.

1. Summary

In April 2021, A DOD HBCU/MSI grant of \$596,000 was awarded to Howard University (HU) for the acquisition of a 3D metal printer and a Fortus 450mc Fused Deposition Modeling printer, to support an ongoing research and pipeline development project in additive manufacturing. The two machines are viewed as a well-integrated equipment set. The printing systems are research focused, production quality machines that allow for the adjustment of production parameters. The equipment is expected to accelerate progress in several active research projects and impact the education and training of several students at HU.

Both the metal and plastic printers were purchased from Amtek Company, Inc. and delivered to Howard University in January 2023. Full installation was done on April 13 and 14, 2023 for the Fortus 450mc polymer printer. Full installation would be done for the metal printer as soon as the necessary fittings and gas tank are installed in the room containing both machines. The equipment along with their accessories will be used to support existing and future projects including the PI's research on "Additive Manufacturing Post Processing Partnership AMP³" funded by Department of Energy. The principal goal of the project is to solidify a sustainable pipeline of under-represented students pursuing Science, Technology, Engineering, and Mathematics (STEM) degrees from Minority Serving Institutes to the National Nuclear Security Agency (NNSA) National Labs and Plants. The AMP³ consortium is the result of productive interaction among HBCUs and DOE-NNSA laboratory and industries occurred during 2013-2019. The equipment will also be leveraged to support research in materials characterization, process parameter optimization, and smart materials with embedded sensors. These are areas of ongoing research, associated with the consortium at Howard University.

The research equipment will facilitate valuable and extensive training of graduate and undergraduate students as well as postdoctoral fellows with broad based knowledge and skills in the area of additive manufacturing so that well-qualified minority graduates can enter the workforce or continue to advance research in areas that are of interest to DoD.

2. 3D Printers and Accessories Purchased (including Discounts)

The grant award was used for the purchase of the state-of-the-art Fortus 450MC printer and Desktop Metal 3D printer. The ongoing research work in the Advanced Design and Manufacturing Laboratory (ADML) at HU requires both polymer and metal parts. No current additive manufacturing machine can produce both types of parts. ADML is located on the ground floor of the Lewis K Downing Engineering Building at HU in Washington, DC. The lab has 1500 sq. ft.

available to house the requested equipment. The Table below shows the various printers and their accessories that had been purchased using this grant.

Item	Price (\$)	Vendor	Status
F450MC PKGEDU: Fortus 450MC GEN II System Package. Fortus 450MC GEN II System (Base Unit), • 16x14x16 inch (406x355x406 mm) Envelope, • Four (4) Material, 1 Year Warranty	241,125	Amtek	Delivered
DM-SS2-EDU: Desktop Metal Studio System 2 EDU Bundle Includes: • Studio System 2 Printer - Bound Metal Deposition TM and Separable Supports TM technology	223,224	Amtek	Delivered
SCA 3600 HT Support Cleaning Apparatus - Recommended for F370 and F270, 1 Year Warranty	9,265	Amtek	Delivered
Edu Discount	-58,969		
SST 1200es P10189 Trade in Discount	-20,000		
Isolation Transformer (200-240VAC 8.0KVA50/60 HZ DELTA-WYE)	2,970	Amtek	Delivered
Isolation Transformer (380-480VAC 8.0 KVA50/60 HZ DELTA-WYE)	2,970	Amtek	Delivered
Discount	-11,261		
Annual Warranty Renewal Partner Emerald Care 450. SC-FDM00029	15,400		
Total	404,724		

3. Fortus 450MC Printer

The Fortus 450mc printer (shown in Figure 1) incorporates the latest in innovative technologies to provide precise prototypes from a CAD design. Stratasys' Fused Deposition Modeling (FDM) technology provides prototype parts, including internal features, which can be used to field-test form, fit, and function. Direct Digital Manufacturing (DDM) allows for the creation of customized end-use parts straight from 3D CAD data. The Fortus 450mc printer is a production quality machine that allows for printing of various thermoplastics including ABS and Nylon. As opposed to lower grade machines, which place a focus on printing conceptual models, the Fortus is designed to produce end-use parts with complex geometries. The accompanying Insight and Control Center job processing and management software provides unprecedented access to build parameters.

The Fortus 450mc printer features a servo/belt driven XY gantry with multiple high temperature modeling material capability. The maximum build area is 16 x 14 x 16 inch (406 x 356 x 406 mm). It has touchscreen graphical user interface. The operating temperature is in the range of 65°F to 86°F (18°C to 30°C), with relative humidity range of 20% to 80% non-condensing. The heat

dissipation occurs mostly through the top of the printer. Heat output is material dependent due to the various temperatures maintained in the build chamber. The printer's power consumption is material dependent due to the various temperatures maintained in the build chamber.



Figure 1: Fortus 450MC Printer

The Insight software provides control for key parameters including tool speed, tool path, build orientation, and polymer porosity. The ability to control process parameters makes the Fortus an extremely strong experimental test bed for exploring FDM capabilities. In addition, the Fortus machines have improved accuracy, speed, and reliability when compared to other machines, such as the Dimension line of FDM printers. This is the result of a stronger frame structure and the

use of improved drive components such as a ball screw drive to control the print heads. Lower grade machines use pulleys.

4. Desktop 3D Metal Printer

The desktop metal 3D printer purchased from Amtek is shown in Figure 2. The printer is similar to the safest and most widely used 3D printing process - Fused Deposition Modeling (FDM). Unlike laser-based systems that selectively melt metal powder, the printer extrudes bound metal rods similar to how a plastic FDM printer works. This eliminates the safety requirements associated with metal 3D printing while opening up new alloys and enabling new features like the use of closed-cell infill for lightweight strength. It has a furnace that sinters the parts. The furnace combines SiC heating elements with high-powered microwaves to sinter printed parts after primary binder is removed. Cloud-connected, the furnace has temperature profiles that are tuned to every build and material. It uniformly heats parts to just below their melting point, removing binder and fusing metal particles to form fully dense parts without the residual stresses introduced in laser-based systems.



Figure 2: Desktop 3D Metal Printer

5. Summary of Projects that would Benefit from the Equipment

The printers along with their accessories will be used to support the following AMP³ consortium projects:

5.1 Dynamic Response of Polymers and Metallic Alloys Fabricated by Additive Manufacturing (Project Manager: Dr. Moses Owolabi, Project Team: Dr. Grant M. Warner, 1 graduate student and 2 undergraduate students)

The ability to fabricate multiscale materials along with multi-functional structures capable of exhibiting a wide range of predetermined physical properties is of great interest. To achieve this type of fabrication using additive manufacturing (AM) technology (also referred to as 3D printing) would represent a significant breakthrough. Traditional polymer AM thermoplastic materials, for instance, acrylonitrile butadiene styrene (ABS), have shown considerable potential primarily due to their mechanical properties, such as impact resistance, toughness, and heat resistance. One drawback of ABS material is the brittle tensile behavior. This brittle behavior is also seen in metallic alloys produced by selective laser melting. In order to reach the goal of multifunctional structural materials with an array of distinctive material properties all fabricated in a single building process, a precise understanding of structure-property-process relationships is required to fully capture the effect of process parameters effecting build orientation (fabrication framework) and physical properties (structural, mechanical, etc.) as a function of geometry. In addition, the microstructure which is contingent upon key fabrication parameters is influenced by the chemical composition and temperature. Therefore, in order to augment or enhance mechanical, thermal, electrical, or dielectric properties by the addition of various nano- to micro-scale fillers, a thorough understanding of the interplay between flow of materials (flowability), cohesiveness and wettability on the outcome of the fabrication process needs to be established.

The achievement pseudo-ductile response in structural configurations motivates the need to gain fundamental understanding of the effect of material fabrication parameters on the response characteristics that may form the basis for this response. Researchers at the Howard University Applied Mechanics and Materials Research Laboratory (AMMRL), in collaboration with Army Research Laboratory (ARL), have investigated both the quasi-static and dynamic response of ABS material fabricated by FDM in limited quantities. Current utilization of ARL and NSC machines makes it prohibitive to perform the experiment at scale. However, initial results of deformation and failure analysis of the 3D printed ABS material under high strain rate loading ($500 - 1000s^{-1}$) indicate what appears to be a pulsating characteristic of ABS material. Its ability to deform until failure may serve as a mechanism to enhance the capability of the material to absorb and deflect energy upon impact until it is completely fractured. In order to further exploit the behavior exhibited in the prior work, structure-property-process relationship of ABS fabricated by FDM must be examined comprehensively, particularly with respect to the effect of build architecture on the dynamic loading response. The equipment will facilitate this research effort.

5.2 Material Property Characterization of 3D printed parts. (Project Manager: Dr. Grant M. Warner, Project Team: Dr. Moses Owolabi (HU), Wesley Everhart (NSC), 2 Graduate Assistants)

Additive manufacturing offers great potential for reducing manufacturing costs, particularly reduced post-production activities since sub-assemblies can be consolidated into a single unit [6]. However, there have been few studies that have tried to address performance characterization comprehensively. Predicting strength, stiffness, fatigue performance is important as it relates to process parameters. Predictive models that characterize the performance of the metals after they have been processed into a part are extremely important for deeper integration of AM parts. It is important to understand what range of chemistries of powder can be processed to produce consistent mechanical properties, what range of parameters can be used to produce consistent mechanical performance, and how many times can powder be recycled before the resulting properties change, etc. In addition, the data needs to be validated by reproducing the same conditions and experiments on multiple machines. The factory of the future consists of rows and

rows of the same “additive” machine, which are able to produce final parts of infinite shapes and configurations. All start with the same powder going in, but each machine will have the potential to process the parts slightly differently at the same settings. Do those subtle variations in laser spot size or melt penetration affect the final mechanical properties of the parts? This can only be determined by the reproduction of the same conditions and experiments on multiple machines.

This project will be directed at the verification of the material properties of additively manufactured parts. This work will leverage ongoing research at the NSC in parameter development and material characterization. Round robin style testing on currently available materials will be performed to evaluate the ability to transfer machine processing parameter sets and build files between nominally identical manufacturing machines. Any differences between the sites will be evaluated and the cause for such differences determined. Material properties to be measured include tensile properties, density, chemistry, fracture toughness, impact properties, and microstructural analysis.

The 3D printing of ASTM D638 of ABS material and metal alloys using a combination of build orientations and raster angles followed by tensile testing at different strain rates (0.5 – 50 cm/ min). The data acquisition of tensile properties such as the high tensile strength, tensile modulus and Poisson’s ratio are used to determine the effects of orientation and strain rates on the quasi-static response. The goal is to consider the build parameters that are likely to affect the properties of rapid prototyped parts with special attention paid to anisotropic effects. As in prior studies, the approach will benchmark the results of several experimental variables including the build direction, and the tool path style on the static mechanical response. Here, the results of quasi-static characterization will be fundamental to the development of optimal configurations for consideration in dynamic testing, where structural tailoring may offer added benefit. These results will feed as input into the dynamic response study outlined previously.

Static and quasi-static testing will be performed at HU and NCAT. Material samples for baseline comparisons will be developed on the requested equipment using parameters provided by NSC. Comparison samples will be developed at NSC. NSC also has ongoing work on material development. It is expected that 4-6 materials will be evaluated over the duration of this project. Additionally, the machine control aspect of characterization will be completed on each piece of AM equipment. This work will be comprised of raking motion, build plate movement and beam characterization. A comparison will be made between the NSC and University equipment to determine any potential calibration issues.

5.3 Achieving desired physico-chemical properties on 3D manufactured components by thin film deposition methods (Project Manager: Dr. Pawan Tyagi, UDC, Project Team: Madhuri Widmer (NSC), 2 undergraduate students)

Achieving needed physico-chemical properties in the targeted areas of a 3D manufactured component will be critical for the DOE specific challenging applications. A specific material used for additive manufacturing may not provide all the desired properties, such as high temperature strength, wear resistance, electrical conductivity, and corrosion resistance etc. There will be a need to bring multiple functionalities on a 3D manufactured component to meet the stringent requirements for challenging applications. One practical approach to produce desired physico-chemical properties on 3D manufactured product is to utilize thin films of different materials and stereo-photolithography. UDC team proposes to use its faculty expertise and thin film deposition capacities to research strategies of depositing thin films on 3D manufactured components to

achieve intended properties. Stereo-photolithography will enable the selection of intended area on a 3D printed component to modify physico-chemical property. Next, the desired material will be deposited by physical vapor deposition and electrochemistry resources at UDC. A 3D printed product coated with suitable materials will have unique engineering characteristics, which otherwise may not be obtained with as produced 3D printed objects.

6. Broader Impacts of the Biaxial Test System

The research equipment, when used along with existing facilities at HU to accomplish the research projects summarized in Section 5, will have broader impacts on the research, education, and training capabilities of HU, the largest HBCU research intensive University in the nation and also the nation's largest on-campus producer of African American PhD degrees. The strategic goal and vision of the College of Engineering is "to become a recognized leader in research and the creation of learning environments conducive to the solution of problems which transcend the boundaries of discipline and profession. Howard University's participation in the AMP3 consortium and research partnerships with ARL will provide access for training to dozens of graduate and undergraduate students from HBCUs in additive manufacturing. AMP³ includes 3 HBCUs each of which will have access to the machine for related projects. Several projects have been outlined in the body of the proposal along with the students expected to be impacted per year. In addition, AMP3 is committed to outreach and summer experiences for both undergraduates and K-12.

7. Management and Maintenance Plan

The co-PI will be responsible for overseeing the management of the requested instrumentation and will work alongside the Department of Mechanical Engineering lab manager. The lab manager has a prior knowledge of material testing and characterization and sound experience in managing a laboratory. The co-PI and the lab manager will be trained by the manufacturer's engineers on how to run and maintain the instrumentation. The cost of installation and training of the PI and the lab manager is included in the pricing for the requested instrumentation.

The Co-PI, Senior Personnel, industrial partners and their graduate/undergraduate students and post-docs will have significant access for the first 12 months of the equipment's operation. To accommodate the need of all users, it is planned to allocate a minimum of 6 weeks to Co-PIs, Senior Personnel, industrial partner and their graduate students and postdocs each year. A portion of time will also be allocated for other faculty, graduate students, and post-docs who may want to use the instrumentation for their course projects and ongoing research. A web-accessible scheduling program will be designed and operated on the College of Engineering computer network to ensure the equipment is in use with minimal downtime for education, training, experimental setup, testing, changeovers, and scheduled maintenance. The PI and the lab manager will administer this.