OFFICE OF NUCLEAR ENERGY

NEET-ADVANCED METHODS FOR MANUFACTURING AWARD SUMMARIES

NUCLEAR ENERGY ENABLING TECHNOLOGIES – ADVANCED METHODS FOR MANUFACTURING

JULY 2019

INTRODUCTION

Advances in manufacturing technologies, including modular construction, improved factory and field fabrication, and other innovative construction technologies are essential to the future of nuclear energy. They are strategically important to the economics of new nuclear power plant construction in the United States and to the competitiveness of the U.S. in the global nuclear energy market.

In 2012, the Nuclear Energy Enabling Technologies (NEET) Program was initiated by the Department of Energy's Office of Nuclear Energy (NE) to conduct research and development (R&D) in crosscutting technologies that directly support and enable the development of new and advanced reactor designs and fuel-cycle technologies. Advanced Methods for Manufacturing (AMM) is one program element of NEET Crosscutting Technology Development. Its focus is to improve the methods by which nuclear equipment, components, and plants are manufactured, fabricated and assembled through the development of new techniques and by utilizing practices found in industries such as oil, aircraft, and shipbuilding.

The NEET AMM program includes two goals:

- Reduce the cost and schedule for new nuclear plant construction
- Fabricate nuclear power plants and their components faster, more economically, and more reliably

By evaluating state-of-the-art practices found in other large manufacturing industries, the nuclear community has identified six major areas of innovation that the NEET AMM program is currently helping to advance. These areas of innovation are:

1. ***Welding and Joining Technologies.*** New technologies focused on high-speed, high-quality and code-acceptable welds are needed in both factory and field fabrications. Electron-beam and laser welding are examples of technologies needed to join heavy section components to improve their efficiency. Online, nondestructive testing that can provide real-time or near real-time feedback on the quality of the weld would improve the productivity in both the shop and the field.
2. ***Additive Manufacturing.*** This process, in contrast with subtractive manufacturing, utilizes lasers, electron beams, friction stir welding, or conventional technologies to fuse thin layers of solid or powdered material in a precise two-dimensional pattern to create a near-net shape component provided by computer-aided design and manufacturing (CAD/CAM) information. Additively manufactured components could provide necessary cost and schedule savings over conventionally manufactured components.
3. ***Modular Fabrication.*** This concept will move new nuclear reactor builds away from piece-built fabrication and construction techniques and allow them to be built economically. The modules must be factory built, transportable, capable of precise placement, engineered to their function in their environment, and easily mated to form a single entity.
4. ***Concrete Materials and Rebar Innovations.*** High-strength, high-performance concrete and rebar will both improve the quality and reduce the construction time required for new nuclear power plants. Advancements that enable integrated prefabrication of reinforced steel-form assemblies will also help to move new builds away from conventional "stick builds."
5. ***Data Configuration Management.*** Complex civil and mechanical designs, and the systems they make up, must maintain their design configuration for the duration of construction and the operational life of the facility. Digital gathering of data and multidimensional data capture are tools that can help maintain that design and assist in design control when modifications are necessary.
6. ***Surface Modification and Cladding Processes.*** Cladding and surface-modification techniques in current nuclear components are typically applied through some form of welding, a process that melts one material into another. This causes unique alloys at the interface. These material differences are the cause of many surface and sub-surface flaws. Avoiding melting by using solid-state, cold-spray, or other bonding processes can eliminate the welded clad problems.

The NEET AMM program is developing these advanced-manufacturing technological innovations through annual competitive solicitations. The program seeks to develop manufacturing and fabrication innovation, assembly processes, and materials innovation that support factory fabrication and expeditious deployment of new reactor builds through the annual Consolidated Innovative Nuclear Research (CINR) Funding Opportunity Announcement (FOA). For more information on this solicitation, please visit www.NEUP.gov. In addition, the Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR) programs target the small business community for manufacturing R&D. For more information on the SBIR/STTR opportunities, please visit www.science.energy.gov/sbir. Projects also create an opportunity to receive funding for access to Nuclear Science User Facilities, if needed, for research and testing. For more information on NSUF projects, please visit https://nsuf.inl.gov.

In Fiscal Year (FY) 2011, before the program initiated, two projects totaling $1,074,251 were selected through the Nuclear Energy University Program (NEUP). The first was awarded to the University of Houston for the development of an innovative seismic-isolation system. The second award was given to the Pennsylvania State University for the study of laser-arc hybrid welding of thick-section nickel-based alloys.

In FY 2012, four projects totaling $3,032,461 were awarded through the CINR solicitation. Two awards were given to the Electric Power Research Institute (EPRI) and Lockheed Martin for the development of powder metallurgy and hot isostatic pressing (PM-HIP) and laser direct manufacturing, respectively. Purdue University received an award to develop modular connection technologies for steel-plate composite walls. Last, an award was given to Idaho National Laboratory for monitoring and control of hybrid laser-gas metal arc welding processes.

In FY 2013, two awards totaling $737,374 were issued through the CINR solicitation to the Georgia Institute of Technology and the University of Houston for the advancement of self-consolidating concrete and ultrahigh-performance concrete, respectively.

In FY 2014, three projects, totaling $2,400,000, were selected through the CINR. The first was awarded to the University of Houston for further development of their FY 2011 NEUP periodic material-based seismic base isolators. Oak Ridge National Laboratory was selected to improve weld productivity by creating a real-time, closed-loop weld-monitoring system. Purdue University received an award to evaluate accident thermal conditions and other parameters on the seismic behavior of nuclear structures. One project was also selected through SBIR solicitation for a Phase II grant totaling $1,500,000. TetraVue, Inc., from San Marcos, California, is looking into high-speed, three-dimensional data capture systems for data-configuration management.

In FY 2015, four projects totaling $3,077,841 were issued through the CINR. Two additive-manufacturing awards were given to General Electric (GE) Global Research and Idaho National Laboratory to investigate irradiation resistance and stress-corrosion-cracking resistance on in-core components manufactured by direct metal laser melting (DMLM) and to develop novel methods for on-site fabrication of continuous large-scale structures, respectively. One award was given to Texas A&M University to develop an advanced surface plasma-nitriding technique. The University of Notre Dame received an award to investigate the use of high-strength steel rebar, prefabrication of rebar assemblies with headed anchorages, and high-performance concrete. Three projects were also selected through the SBIR solicitation, totaling $1,299,579. RadiaBeam Systems from Santa Monica, California, will look to join austenitic steels to nickel-based superalloys through electron beam melting. Voxtel, Inc. from Beaverton, Oregon, was looking into data-configuration management systems. Both RadiaBeam and Voxtel received Phase II SBIR awards of $1 million each to continue their work.

In FY 2016, the program funded four projects totaling $2,798,928. ORNL is developing an all-position surface-cladding and modification system using solid-state friction stir additive manufacturing. Idaho State University is investigating ways to enhance the irradiation tolerance of steels using an innovative manufacturing technique to achieve nanostructuring. EPRI and collaborators are pursuing the ability to rapidly qualify components made by laser-based powder-bed additive manufacturing using integrated computational materials engineering. Irradiation-performance data for stainless steel and Inconel produced by commercially-available additive manufacturing techniques is being gathered by the Colorado School of Mines.

In addition, EPRI is testing new manufacturing technologies with the goal of producing a two-thirds scale SMR reactor pressure vessel as part of a $2,500,000 directed research program awarded in FY 2017. The project builds on EPRI's earlier Department of Energy-funded research and development of a PM-HIP process.

A program funded in FY 2018 for $1 million is enabling the University of Wisconsin to investigate cold-spray additive manufacturing of oxide-dispersion strengthened (ODS) steel cladding tubes and as a surface-modification technology. NovaTech received Phase 2 SBIR funding to use 3D printing to produce hold-down springs and bottom nozzles for boiling-water reactor (BWR) fuel assemblies. In a Phase 2 SBIR project, Mainstream Engineering is using its Electron Beam-Enabled Advanced Manufacturing Facility to explore manufacturing small modular reactor (SMR) components made of 316L stainless steel.

As part of the Industry Funding Opportunity Announcement, three cost-sharing awards were announced in FY 2018. BWX Technologies, Inc., (BWXT) will establish an integrated advanced-manufacturing and data-science-driven paradigm for advanced reactor systems. Holtec will receive funding to advance and commercialize a technology known as hybrid laser-arc welding for use in nuclear structures and systems. EPRI will proceed with plans to develop an in-chamber electron-beam welding system.

Also funded in FY 2018, Argonne National Laboratory received $1 million to study the use of pulsed thermal tomography for nondestructive evaluation of reactor materials and components. In another $1 million project starting in FY 2019, the University of Pittsburgh is pursuing a drastic reduction in the development and post-processing costs associated with laser powder-bed additive manufacturing of complex nuclear reactor components with internal cavities and overhangs. The Massachusetts Institute of Technology received $469,321 to obtain critical performance data for three promising SiC joint formulations, and to use these results to generate a material properties database to enable more accurate modeling of SiC joints.

Several SBIR projects were funded in FY 2018 and are now a part of the AMM portfolio. Brimrose Technologies is exploring an ultrasonic-scattering inspection approach for improved AM. LER Technologies is pursuing real-time, nondestructive evaluation during 3D manufacturing of metal parts. PolarOnyx is developing a controllable 3D manufacturing system. Aeroprobe received funding to evaluate the performance of 316L stainless steel produced by two additive manufacturing processes: laser powder-bed fusion and MELD, a friction stir method. All are Phase 1 projects.

Since 2011, the AMM program has awarded a total of almost $40 million for 38 projects. These open, competitively selected awards have already begun to make significant progress in the advancement of manufacturing technologies. Each year, the participation in the solicitations has grown to include more partnerships and include a more-diverse selection of industries applying their technology to the nuclear energy sector. In the following sections, it will be seen that the developments and innovations continue to surpass the expectations of the NEET AMM program.

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ADDITIVE MANUFACTURING AWARDS

Establishment of an Integrated Advanced Manufacturing and Data-science-driven Paradigm for Advanced-reactor Systems

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Dr. Xin Sun and Dr. Michael Kirka, Oak Ridge National Laboratory
Funding: $7,915,014 (08/01/2018 – 07/31/2020)

Description of Project: BWX Technologies Nuclear Energy, Inc., (BWXT) in collaboration with Oak Ridge National Laboratory (ORNL), is developing the ability to implement additive-manufacturing (AM) technologies using high-temperature alloys in the design and manufacturing of nuclear components. To accomplish this, the research team is establishing an integrated three-dimensional (3D) design, build, and test paradigm, informed by data science (Figure 1.), for advanced-reactor systems. Using a combination of *in situ* process-monitoring technologies, modeling, and data analytics, the project aims to develop AM processing parameters for Hastelloy X and molybdenum-based alloys for use in nuclear reactor systems and subsystems and to investigate component-level qualification processes for the future certification of nuclear materials configured in complex geometries. The project scope consists of conceptual design and analysis of complex nuclear component geometries, AM of complex geometries using Arcam electron beam melting (EBM) technology, *in situ* monitoring to create digital representations of builds, destructive and nondestructive examination (NDE) to benchmark a data-science framework and demonstrate the mechanical strength of AM high-temperature alloys, and the development of a commercialization plan for future nuclear design and manufacturing.

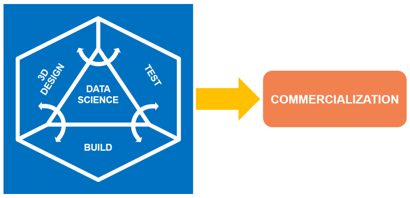

Figure 1. Integrated 3D design, build, test paradigm informed by data science.

Impact and Value to Nuclear Applications: AM technologies can be transformational for the nuclear industry because they are capable of producing geometries not possible with conventional manufacturing techniques. Additionally, proving the ability to AM high-temperature alloys enables designs that possess improved thermal-energy management, increased safety margins, and accident-tolerant characteristics. The choice of Hastelloy X and molybdenum-based alloys bounds advanced-reactor technologies both in operating temperature and coolant type, allowing the results of this project to potentially benefit a wide spectrum of advanced reactor designs. Additionally, a breakthrough in the proposed AM development and the integrated 3D design, build, test paradigm, with regard to molybdenum, could have an immediate impact on the current commercial-reactor fleet and the endeavor for an accident-tolerant fuel design.

Recent Results and Highlights: At this stage of the project, all planned milestones—including the receipt, installation, and site-acceptance testing of the Arcam EBM Spectra H machine (Figure 2)—have been met. The first iteration through the 3D design and build process of complex nuclear-component geometries with Hastelloy X was completed (Figure 3), and digital part reconstruction using the data-science framework was successfully demonstrated. Last, AM development for molybdenum began focusing on process parameters, thin-wall builds, and mechanical properties (Figure 4). Near-term future work scope includes NDE, destructive examination, and mechanical testing of the completed Hastelloy X builds, starting the second iteration of the integrated 3D design, build, test process, and continuing to work through molybdenum process-parameter development.

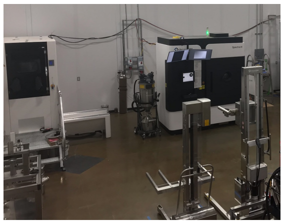

Figure 2. Arcam Spectra H installed at ORNL-Manufacturing Demonstration Facility

Figure 3. Hastelloy X thin-wall test builds

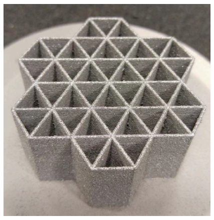

Figure 4. Molybdenum test build

Irradiation-performance Testing of Specimens Produced by Commercially Available Additive-manufacturing Techniques

Jeffrey C. King, Colorado School of Mines

Funding: $2,529,985 (10/01/16 - 09/30/20)

Description of Project: This project will collect irradiation-performance data for stainless steel and Inconel specimens produced using commercially available AM techniques. Test specimens have been harvested from billets produced by several AM techniques. The Colorado School of Mines is conducting pre-irradiation thermomechanical testing (of tensile and yield strength, elastic modulus, ductility, thermal conductivity and diffusivity) and microstructural characterization of unirradiated specimens. The Advanced Test Reactor (ATR) irradiated a second set of specimens at typical light-water reactor (LWR) temperatures. A comparison of the physical properties and microstructure of the irradiated specimens to those of the as-fabricated specimens will provide insight into the viability of additively manufactured parts for nuclear reactor applications, identify key areas of concerns for further technology development efforts, and provide data for future computational-model development.

Impact and Value to Nuclear Applications: Despite the potential benefits, the deployment of AM technologies to support the nuclear energy industry is limited by two things: (1) a lack of characterization and property data for parts produced by different AM techniques, which limits the ability of additively manufactured parts to meet nuclear quality assurance requirements and (2) a lack of data related to the irradiation and performance of additively manufactured parts, which limits confidence that these parts can survive in the challenging environments needed for nuclear energy applications. This project will produce data to address both of these challenges.

Recent Results and Highlights: Pre-irradiation testing of the additively manufactured samples is complete, and microstructural characterization is underway. Figure 1 shows the stress-strain curves produced for unirradiated stainless steel samples. The behavior of the unirradiated specimens is similar to that of conventionally produced wrought stainless steel. Transmission electron microscopy of the unirradiated heat-treated stainless steel specimens identified stacking fault structures that had not been previously identified in existing literature (Figure 2). The project is considering the potential impact of these structures on the irradiation performance and stability of these structures under irradiation. Irradiation is complete and post-irradiation thermomechanical testing and microstructural characterization began at the Nuclear Science User Facilities (NSUF) post-irradiation examination facilities in June.

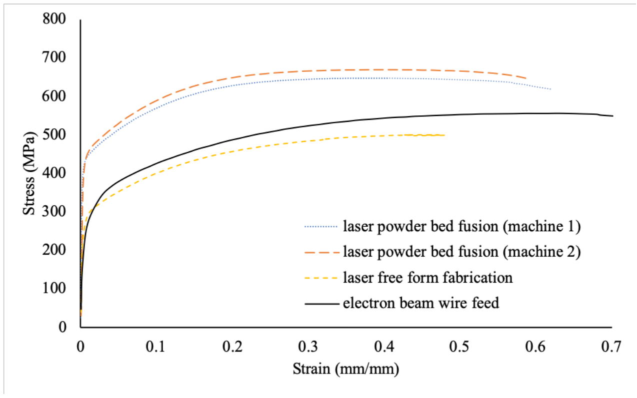

Figure 1. Stress-strain curves for the unirradiated stainless steel samples.

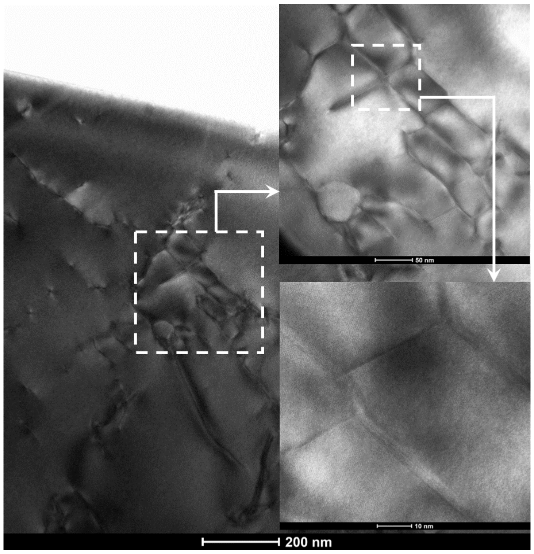

Figure 2. High-resolution transmission electron images of unirradiated additively manufactured stainless steel 316L after heat treatment, showing a stacking fault structure not found in existing literature.

Enhancing Irradiation Tolerance of Steels via Nanostructuring by Innovative Manufacturing Techniques

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Funding: $500,000 (10/01/2016 – 09/30/2023, coupled with NSUF facility access)

Description of the Project. This project involves pre-irradiation characterization, neutron irradiation, and post-irradiation examination of bulk nanostructured austenitic and ferritic/martensitic (F/M) steels, which are anticipated to have enhanced irradiation tolerance. The steels are produced by two innovative, low-cost manufacturing techniques: equal-channel angular pressing (ECAP) and high-pressure torsion (HPT). The objectives are to enhance our fundamental understanding of irradiation effects in ultrafine-grained (UFG, 100 nm < grain diameter < 1 µm) or nanocrystalline (NC, grain diameter <100 nm) steels produced by ECAP or HPT, and to assess the potential application of ECAP and HPT to fabricate materials for current and advanced reactors. Improving the performance of currently used austenitic and F/M steels through microstructural engineering via advanced manufacturing techniques possesses the potential to improve radiation tolerance at a relatively low cost compared to the development of new alloys.

Impact and Value to Nuclear Applications. The outcomes of this research will be feasibility assessment of applications of two low-cost advanced-manufacturing techniques (i.e., ECAP and HPT) in fabricating materials with improved performance for current and advanced reactors, with an established and enhanced understanding of the irradiation effects in UFG and NC F/M steels. The application of low-cost AM techniques in fabricating currently used materials in LWRs and advanced reactors to achieve microstructural engineering and improved performance will contribute to the life extension of LWRs and facilitate development of advanced fast reactors. Hence, the research is anticipated to have significant impact on nuclear energy R&D.

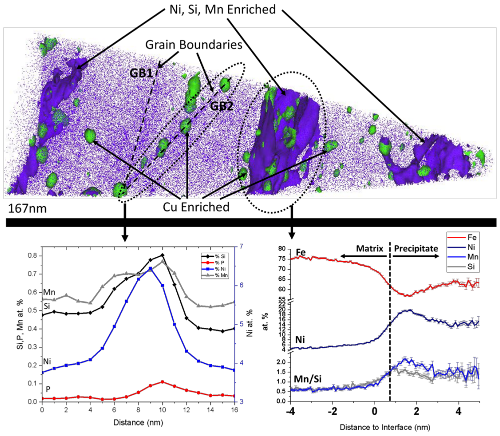

Figure 1. ATP reconstruction of 304 steel after HPT showing Ni atoms (blue), Ni-enriched precipitates (blue), and Cu precipitates (green).

Recent Results and Highlights. Pre-irradiation characterization was performed on bulk nanostructured austenitic (304 and 316) and F/M steels (Grade 91 and Kanthal D) manufactured by ECAP and HPT. Through atom probe tomography (APT), unique grain-boundary segregation was observed in HPT304. This segregation led to the formation of Ni-Mn-Si precipitates along grain boundaries as well as the formation of Cu precipitates near and along these boundaries. This enhanced segregation and precipitation after severe plastic deformation was also observed in Kanthal-D. In the Kanthal-D samples, Cr enriched $M_{23}C_6$ carbide was observed after both ECAP and HPT at elevated temperatures, while the same precipitation was not found during annealing at the same temperature of the coarse-grained counterpart. Thermal stability was also compared between all sample sets, which showed that the nanostructured austenitic steels have much higher thermal stability than the ferritic steels. ECAP manufactured materials show better thermal stability than HPT manufactured samples. This has been attributed to the high number fraction of low-angle grain boundaries and lower strain energy in the ECAP samples as compared to HPT samples. All steel samples went into the ATR at Idaho National Laboratory in June 2018 for neutron irradiation.

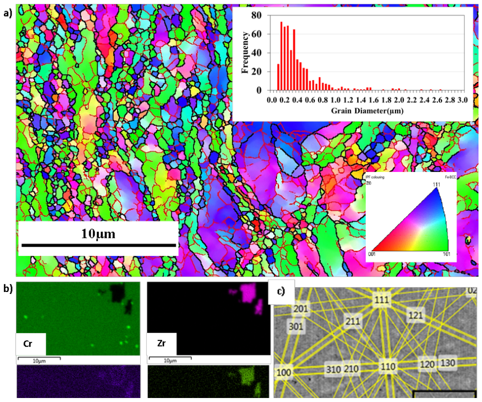

Figure 2. a) Electron backscatter diffraction, b) energy-dispersive spectroscopy maps of ECAP Kanthal-D, and c) indexed kikuchi pattern showing $M_{23}C_6$ structure.

Pulsed Thermal Tomography Nondestructive Examination of Additively Manufactured Reactor Materials and Components

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Mr. William Cleary, Westinghouse Electric

Funding: $1,000,000 (10/01/2018 – 09/30/2021)

Description of Project: We are developing pulsed thermal tomography (PTT) architecture and algorithms for nondestructive evaluation of additively manufactured reactor components. PTT obtains reconstruction of material internal defects by monitoring surface temperature transients following a thermal pulse applied to material surface. The method is noncontact, performed from stand-off distance, measured from one side of the specimen. An imaging camera with a megapixel array of detector elements acquires an image of a large section of material. This allows for the detection of flaws with a minimal amount of mechanical scanning, in contrast with image acquisition, which requires point-by-point raster scanning of specimens. A photograph of the laboratory PTT system setup is shown in Figure 1.

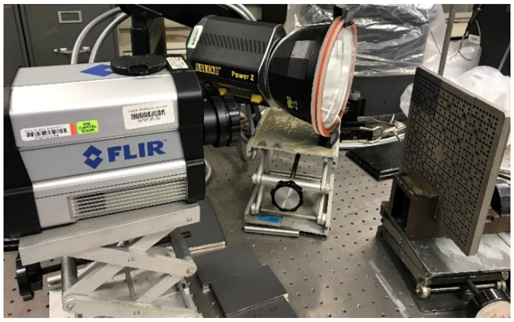

Figure 1. Photograph of the PTT laboratory system

Impact and Value to Nuclear Applications: AM is expected to play an increasing role in nuclear energy sustainability and cost reduction. However, because of stringent safety requirements, the long-term performance of AM-printed reactor components needs to be investigated before AM is widely accepted. Monitoring the integrity of AM components requires development of advanced NDE methods. Because of the complex shapes and significant surface roughness of components due to layer-by-layer welding processes in AM, conventional methods might not be useful for NDE of AM structures.

Recent Results and Highlights: Capabilities of PTT were evaluated by performing tomographic imaging of an Inconel 718 (IN718) nozzle plate produced using the direct laser sintering AM method. The plate is 17 mm thick, with an approximately 8 inch by 8 inch cross-section. A photograph of the nozzle plate is shown in Figure 2. Distribution of incident thermal pulse on the plate is not uniform because the flash illuminates the metallic plate at an angle. To compensate for this, researchers fitted the intensity distribution in the camera frame, containing a flash with a polynomial, and then used this polynomial for correction of the image intensity in every subsequent frame. The plates were imaged with a 320 × 256 array of pixels at 200 Hz resolution rate. Figure 2 shows a zoomed-in reconstruction of a smaller area of the IN718 plate. The left plane of the figure shows a parallel plane reconstruction at 1 mm depth. Two horizontal lines labeled j = 80 and j = 165 correspond to the indices of rows of the 320×265 array of pixels in the imaging camera. Vertical cross-section plane reconstructions corresponding to lines j=80 and j=165 are shown in the right plane of Figure 2. An important feature is that the front top and back surfaces of the IN718 nozzle plate are distinguishable in both images. This shows that PTT is capable of imaging through a 17 mm thick plate. Total imaging time was 20.93 seconds.

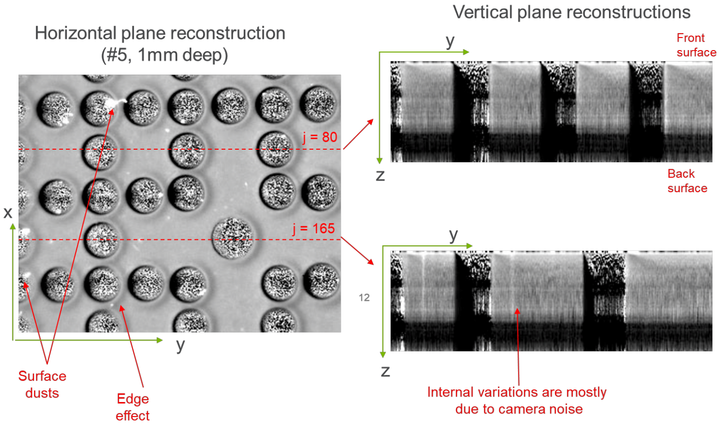

Figure 2. Zoomed-in reconstruction of IN718 nozzle plate (left). Horizontal plane reconstruction at 1 mm depth. Vertical cross-section plane reconstructions (right).

Development of Low-temperature Spray Process for Manufacturing Fuel Cladding and Surface Modification of Reactor Components

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Dr. Peter Hosemann, University of California-Berkeley

Dr. David Hoelzer, Oak Ridge National Laboratory

Dr. Stuart Maloy, Los Alamos National Laboratory

Dr. Patrick Grant, Oxford University

Funding: $1,000,000 (10/01/2017 – 09/20/2020)

Description of Project: Cold-spray AM is being investigated in this project as a method for manufacturing oxide-dispersion strengthened (ODS) steel cladding tubes and as a surface modification technology to mitigate corrosion and wear in reactor components in future conventional and advanced nuclear reactors. Cold spray is a high-velocity, solid-state spray process that operates by propelling powder particles onto a substrate to create a deposit or a coating. Because cold spray is a solid-state process, no melting of the powder particles occurs, making the process ideal for fabrication of ODS steel cladding tubes, where the melting processes will lead to upward stratification of oxide nanoparticles.

Impact and Value to Nuclear Applications: The project introduces a low-temperature solid-state process for the rapid manufacturing of components for the nuclear industry while significantly adding to the components' value by lowering cost and improving properties. In the case of ODS steel cladding, the cold-spray approach obviates the need for multiple extrusion and annealing steps currently used to manufacture tubes. Likewise, cold spray offers a low-temperature surface coating approach for improving wear and corrosion resistance of nuclear reactor components without thermally inducing microstructural changes in the substrate material. It is anticipated that this approach will also enable the near-term deployment of materials in nuclear reactors, which are currently either not cost-competitive to manufacture or are restricted by scientific barriers in conventional manufacturing processes.

Recent Results and Highlights: This project has successfully manufactured a free-standing, eight-inch ODS steel cladding tube, shown in Figure 1, using the cold spray process. A gas-atomized 14YWT powder was cold-sprayed onto a rotating cylindrical aluminum alloy substrate and produced a 1 mm thick and dense deposit. The deposit was polished, and the aluminum-alloy tube was removed by dissolution to leave a free-standing ODS steel cladding tube. Multiple post-deposition heat treatments were investigated, and a vacuum heat-treatment process at 1000°C for one hour was chosen as the most promising method to achieve the last remnants of densification and recrystallization and to induce oxide particle precipitation. However, a grain growth was observed in the cladding tube after this process. Future work will focus on using gas-atomized 14YWT powder with higher yttrium and oxygen content to precipitate a higher-number density of oxide nanoparticles after the post-deposition heat treatment to pin grain boundaries and reduce grain size. Separately, an oxidation-resistant FeCrAl alloy coating was successfully deposited by the cold-spray process on the aforementioned ODS steel tubes, thus validating an approach for achieving a combination of high-temperature strength and oxidation resistance using the cold-spray process.

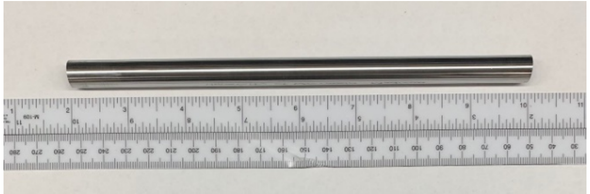

Figure 1: Photograph of free-standing ODS steel cladding tube produced by cold spray process.

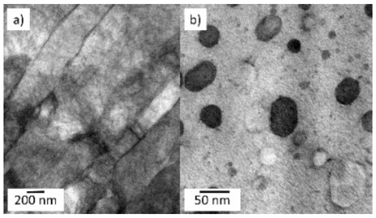

Figure 2: Scanning transmission electron microscopy (STEM) image of ODS steel cladding tube (a) as-deposited and (b) heat treated at 1000 ℃ for 1 hour.

Integrating Dissolvable Supports, Topology Optimization, and Microstructure Design to Drastically Reduce Costs in Developing and Post-processing Nuclear Plant Components Produced by Laser-based Powder-bed Additive Manufacturing

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Dr. Wei Xiong, University of Pittsburgh
Dr. Owen Hildreth, Colorado School of Mines

Funding: $1,000,000 (10/01/2018 – 09/30/2021)

Description of Project: This project aims to develop and establish an innovative approach to drastically reduce development and post-processing costs associated with laser powder-bed AM of complex nuclear reactor components with internal cavities and overhangs. The proposed innovative approach integrates dissolvable supports, topology optimization, and microstructure design to achieve the project goal. The proposed research will (1) develop and validate recipes to dissolve support structures and reduce surface roughness using the PIs' self-terminating dissolution process, (2) develop an automated support structure design tool capable of maximizing the support dissolution rate and minimizing residual stress and distortion of AM parts, (3) design AM processing with post-heat treatment to optimize hierarchical structure of AM parts by applying integrated computational materials engineering (ICME) modeling, (4) design surface heat treatment recipes for enhanced mechanical property, and (5) demonstrate that the integrated technology is capable of removing internal support structures, not assessable by post-machining, for two complex nuclear reactor components in less than 24 hours.

Impact and Value to Nuclear Applications: The proposed dissolvable-support-based technology is expected to have a huge impact on the nuclear industry. Using optimally designed dissolvable supports, this research will make state-of-the-art nuclear components much cheaper, have minimal distortion, and eliminate build failures altogether. The proposed technology will enable consolidation of many manufacturing steps currently required for complex nuclear components into one AM assembly, which would reduce manufacturing costs by at least 20%, improve manufacturing schedules by at least 6 months, and preclude unforeseen delays. Additionally, post-processing accounts for 70% of the cost of producing AM products, with support removal accounting for the majority of those costs. This work will help bring dissolvable supports, not just to nuclear applications, but to the broader metal AM community so that AM costs can be significantly reduced.

Recent Results and Highlights: Thus far, the team has (1) developed a detailed thermal-process simulation model for 316L and 17-4PH (see Figure 1) with experimental calibration- and validation-obtained preliminary results on inherent strains for the two stainless steels, (2) developed the recipe-optimization process (see Figure 2) and achieved Ra roughness down to 2.4 µm, (3) performed calculations of the heat-treatment processing map and step diagram of Stellite 6 cobalt alloy, and (4) established a preliminary ICME model framework for post-heat treatment of steels based on the process-structure-property relationships.

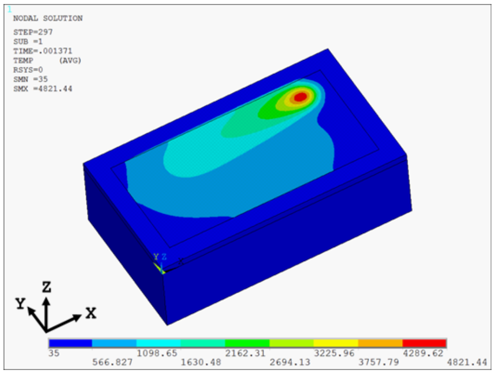

Figure 1. Snapshot of detailed process simulation of the laser powder-bed fusion process.

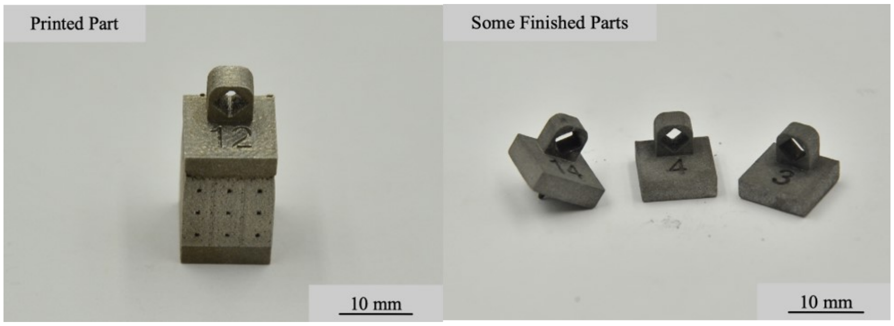

Figure 2. Illustration of the dissolvable support structures.

Real-time Nondestructive Evaluation during 3D Manufacturing of Metal Parts

Araz Yacoubian (PI), Wen Wang, Gary Winter, Paul LoVecchio, Ler Technologies, Inc. Encinitas, CA

Funding: $149,995 (07/02/2018–05/31/2019)

Description of Project: AM, such as laser sintering or melting of additive layers, can produce parts rapidly at small volume and in a factory setting. To make parts of nuclear quality, a real-time nondestructive examination technique is required to detect defects while they are being manufactured. The proposed nondestructive evaluation technique is a feasibility study of a sensor unit that is incorporated into a direct metal laser-sintering machine to capture defects in real time. The sensor data can be used to identify defects as they occur so that immediate corrective action can be taken. It also provides parameters that enable prediction of whether the part is of nuclear quality. The final outputs of the sensor unit produce a defect map in real time as the part is being printed. Defects such as voids, improper melting, bulging of the metal, and out-of-spec prints are revealed.

Impact and Value to Nuclear Applications: When this NDE technology is commercialized, the sensor unit will be incorporated into 3D printing machines without requiring design changes to the machine. The sensor data will be utilized to prequalify parts for nuclear quality, thereby minimizing or eliminating the need for post-fabrication testing. The economic benefits include reduction in the cost of post-process testing and significant reduction of the loss of labor and material due to faulty parts. The Department of Energy and other government entities will benefit by streamlining the manufacturing of nuclear parts. The reduced cost of manufacturing will help the transition to modern nuclear energy, which will benefit the public by providing safe and cost-effective energy.

Recent Results and Highlights: Samples were designed and fabricated to contain representative defects that occur during AM. The samples were tested using the proposed approach. Data obtained from the tests revealed defects that matched those on the samples and demonstrated the feasibility of using a multiparameter NDE approach. A defect-detection example is shown in Figure 1. One of the challenges of real-time defect detection in a metal-printing environment is the presence of various types of noise. To ensure that the proposed approach is suitable for this environment, work was performed and noise reduction was successfully demonstrated via a set of simulations and experiments.

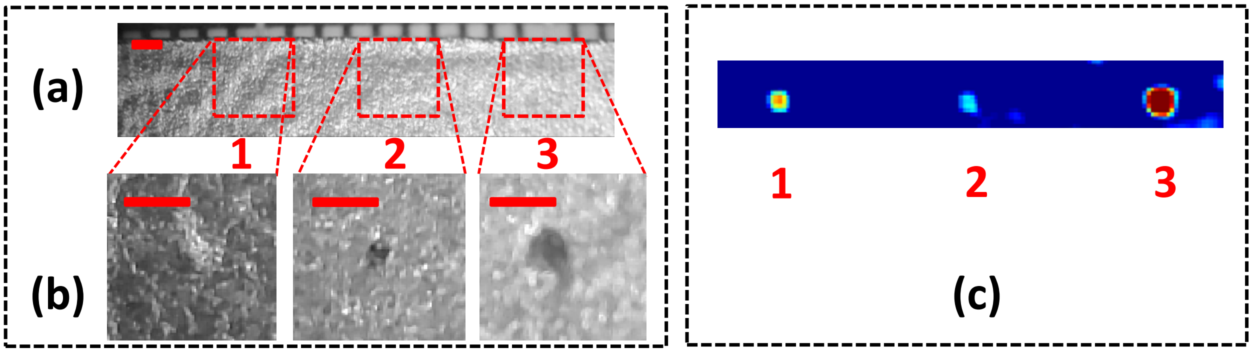

Figure 1. a) Microscope image of direct metal laser-sintering-fabricated sample containing three defects of different sizes. b) Detail of the defects. c) Sensor output showing Defects 1, 2 and 3 that are difficult to see even with a microscope. Red scale bars in (a) and (b) are 1 mm.

Controllable 3D Manufacturing System

Dr. Jian Liu (Principal Investigator), Dr. Shuang Bai, Mr. Kenny He, Mr. Patrick Lee
PolarOnyx, Inc. Funding: $150,000 (07/02/2018 - 04/01/2019)

Description of Project: The next generation small modular reactors (SMRs) requires new and improved techniques, instrumentation, and strategies to deal with anticipated high-radiation and high-temperature environments. Component-manufacturing technologies will be required that take full advantage of the new 3D printing methods such as AM technologies. These manufacturing methods must be capable of producing components or subcomponents on a limited-production basis and with nuclear quality.

Based on its success in developing a variety of award-winning high-energy and high-power ultrafast fiber lasers and pioneering work in full-spectrum (fs) laser 3D manufacturing (US patents, 9643361 and 9770760), PolarOnyx proposes to use tunable fiber lasers to develop a smart AM and subtractive manufacturing (SM) system to make nuclear quality components for SMRs. This all-in-one multifunctional capability (SM and AM, controllable laser energy/power, controllable melting temperature and heat-affected zone) is not achievable for continuous-wave laser AM and will significantly reduce building time and cost. Its material-absorption-independent feature opens a new and unprecedented opportunity for multi-material 3D manufacturing. By integrating with fs laser SM, layer-by-layer processes can be done to micron-level precision, so a complex shape with fine structure is achievable.

Impact and Value to Nuclear Applications: The project introduces a smart 3D-manufacturing system to make nuclear quality components without going through many iterations. This is the enabling technology that will significantly reduce cost and turnaround time, with the capability of detection, characterization, and trimming of defects. Note that the parts made with conventional AM systems need post-processing to polish, anneal, cut, trim, and structure. This significantly introduces extra labor and cost. Moreover, a lack of efficient ways to detect defects, cracks, surface roughness, and alloy composition before, during, and after processing creates challenges for components made for SMRs with existing 3D printing systems in withstanding higher operating temperatures and plasma radiation while, at the same time, maintaining stability, environmental resistance, and mechanical properties.

Recent Results and Highlights:

- Developed and investigated infrared (IR) thermal image, laser-induced breakdown spectroscopy (LIBS), and a high-resolution visible camera as a powerful tool to characterize true thermal distribution, roughness, and defects.
- Filed a patent (Application number 16378485) for integrating IR and visible images and LIBS for intelligent AM system.
- Developed a control algorithm and proved it works well for an overhang experiment.
- Achieved high-density (i.e., >99%) and excellent mechanical properties.
- Succeeded in developing a working, reliable calibration method to extract true temperature distribution during AM process.

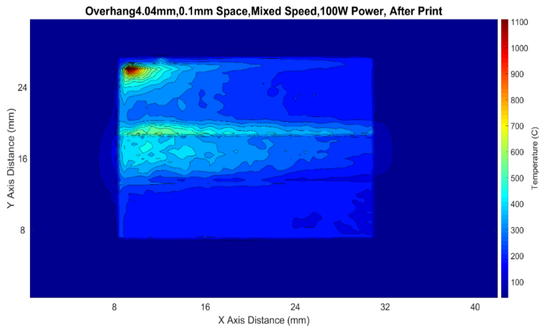

Figure 1. True-temperature extraction after emissivity correction with accurate surface roughness measurement. It clearly shows the true temperature-distribution, boundaries of various sections, and defects.

3-D Printing of Nuclear Fuel Assembly Nozzles and End-Spacer Grids

George Pabis (Principal Investigator), Innovative Technologies International, Inc.

Funding: $1,118,995 (06/13/2016 – 07/30/2019)

Description of Project: Direct metal laser sintering AM will be used to fabricate bottom nozzles with debris-filtering and fuel-rod capture features. AM (e.g., 3D printing) is becoming more common as a manufacturing option in other industries, and this project is meant to prove that this technology is a viable option for fabrication of fuel-assembly components. The material properties for 3D-printed material will be compared to wrought material properties. The nozzle design will be tested in a flow loop to determine pressure-drop characteristics and debris-capture capabilities. At the end of the Phase II project, a new nozzle design, fabricated using AM, should be ready for insertion into a commercial reactor for final testing prior to batch implementation.

Impact and Value to Nuclear Applications: The AM process allows a designer to consider more-complicated geometries that can improve flow characteristics and debris-capture ability of the bottom nozzle. The bottom nozzle can also incorporate fuel-rod locking features that may make it possible to eliminate the bottom grid on the fuel assembly, thus reducing cost.

Recent Results and Highlights: In Phase I, additive manufactured Inconel 718 material samples were tested to determine their yield and ultimate strength, which were compared to wrought-material properties. For Phase II, 3D-printed samples are being irradiated in the High Flux Isotope Reactor; afterward, material properties will be tested and compared with irradiated wrought-material properties. In Phase I, multiple debris filters were designed and printed as 5 × 5 sections of the nozzle. These sections were tested to determine pressure drop for the various designs. The test results show that debris filtering could be successfully achieved over a broad range of pressure drops, providing designers with the ability to tune the pressure drop of the bottom nozzle to achieve optimal performance. In Phase I, the fuel-rod locking mechanism was also tested to characterize its capture strength. For Phase II, the focus has been to develop a full-size bottom nozzle for testing in a flow loop. The optimal debris-filter designs from Phase I were used to develop a nozzle that incorporates guide-tube connections and support legs for a full-size nozzle. Figure 1 shows a quarter section of the nozzle—the part includes the guide-tube connection holes and the bottom foot. The full-size part, printed from Inconel 718, will be tested in a full-size loop that is currently under construction at NovaTech. A small flow loop at NovaTech is also being modified in order to perform vibration tests with 5 × 5 short fuel assemblies. The tests will be used to compare fuel-rod vibration behavior between the current configuration, which includes a bottom grid, and a new configuration with fuel rods locked in the bottom nozzle and no bottom grid.

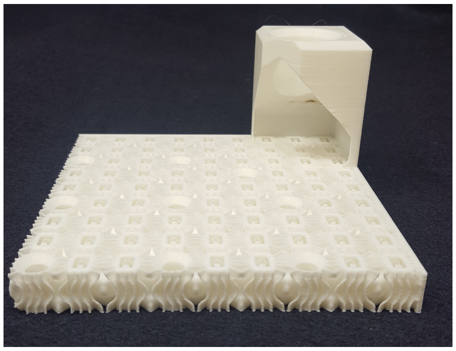

Figure 1. Photograph of 1/4 section of the bottom-nozzle concept.

Additive Manufacturing of High-strength Stainless Steel Components for Small Modular Reactors

Dr. Ryan D. Reeves (Principal Investigator), Mainstream Engineering Corp.

Dr. Justin J. Hill, Mainstream Engineering Corp.

Funding: $999,917 (08/27/2018 – 08/26/2020)

Description of Project: This project investigates the effect of AM of 316L stainless steel using ultrahigh-energy electron beams. We have commissioned a first-of-its-kind Electron Beam-Enabled Advanced Manufacturing Facility (EBEAM), powered by a superconducting linear electron accelerator to generate an electron beam with energies as high as 1.4 MeV (Figure 1). In Phase I, researchers successfully additively manufactured 316L from powder, but were limited by beam-control instabilities. In Phase II, researchers are enhancing beam controls and automation to improve the AM capabilities of the EBEAM system. The research plan is to study the effect of neutron radiation on the strength and fracture toughness of additively manufactured 316L and compare this effect to cast and annealed 316L. Finally, additively manufacture 316L stainless steel prototype SMR nozzles will be tested for fatigue strength and radiation tolerance.

Impact and Value to Nuclear Applications: AM is expected to substantially reduce deployment times of SMRs. Some estimates predict that deployment schedules could be accelerated by up to six months while component fabrication costs are reduced by 20% or more through the adoption of advanced and additive manufacturing innovations. Mainstream Engineering has introduced a new dimension to additive manufacturing through its EBEAM. This ultrahigh-energy system produces an electron beam with 20 times the energy of other additive manufacturing systems, allowing for far-from-equilibrium material processing. This capability can impart additional functionality to components through microstructure refinement, including increased strength, tailored anisotropy, increased hardness, and improved wear resistance.

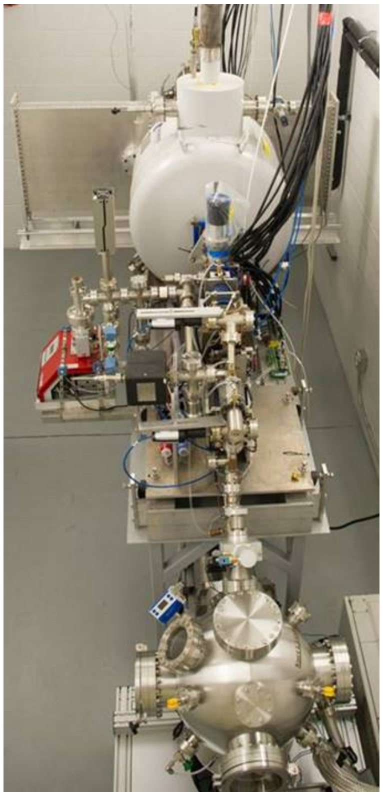

Figure 1. EBEAM system for additive manufacturing of SMR components housed at Mainstream Engineering Corp. in Rockledge, FL. Electron beam energies exceed 20× higher than any other AM system.

Recent Results and Highlights: The initial focus of the project has been to improve the control of the electron beam current and energy. The system, as commissioned, produced a high-energy electron beam that fluctuated ±9% of the current set point and ±13% of the electron-energy set point. By modifying and upgrading the electrical hardware, researchers have reduced the current fluctuations to ±3% and the electron energy to ±5%. This is expected to substantially improve AM resolution and repeatability. Further improvement to beam controls through upgraded control circuitry and logic is expected. Improving the AM automation of the powder bed to accelerate build times and improve consistency is underway. Preliminary AM samples exhibit improved melt consistency with fewer voids and higher uniformity. Currently, characterization of the unique microstructure of samples results from the ultrahigh-energy electron beam and far-from-equilibrium processing. This includes studying crystallographic, elemental, and mechanical properties of the additively manufactured samples. Upon completion of system modifications, researchers will additively manufacture prototypes and test coupons to undergo mechanical and radiation-exposure testing.

MODULAR FABRICATION AWARDS

Small Modular Reactor Pressure-vessel Manufacturing and Fabrication-technology Development

D. Gandy and M. Albert, Electric Power Research Institute

W. Kyffin and M. Cusworth, Nuclear-Advanced Manufacturing Research Centre

Funding: $2,500,000 (10/01/2017–09/30/21)

Description of Project: Many of the same manufacturing and fabrication technologies that were employed for LWR plants built 30–50 years ago are being employed today to build advanced LWRs (ALWRs). Manufacturing technologies have not changed dramatically for the nuclear industry even though higher-quality production processes—which could be used to significantly reduce overall component manufacturing and fabrication costs—are available. New manufacturing and fabrication technologies that can accelerate production and reduce costs are vital for the next generation of SMRs and Advanced GEN IV plants to assure they can be competitive in current and future markets. This project was assembled to test and prove acceptable several new manufacturing and fabrication technologies with a goal of producing critical assemblies of a two-thirds scale demonstration SMR reactor pressure vessel (RPV).

Impact and Value to Nuclear Applications: Through the use of technologies including electron-beam welding (EBW), powder metallurgy-hot isostatic pressing (PM-HIP), diode laser cladding, and advanced machining, EPRI and the United Kingdom's Nuclear-Advanced Manufacturing Research Centre (Nuclear-AMRC) will demonstrate that critical sections of an SMR can be manufactured and fabricated in fewer than 12 months at an overall cost savings of >40% (versus today's technologies). The project aims to demonstrate and test the impact that each of these technologies would have on future production of SMRs and to explore the relevance of the technologies to the production of ALWRs, SMRs, GEN-IV, ultra-supercritical fossil, and supercritical CO_2 plants.

Recent Results and Highlights: In 2018, excellent progress was made in SMR manufacturing and fabrication, including (1) development of EBW parameters for thick-section SA508 components, (2) evaluation of diode laser cladding parameters for welding the filler metals ER308L and Alloy 82, (3) completion of a 1.8 m diameter × 75 mm thick SA508 weld in 47 minutes in the NAMRC's electron-beam vacuum chamber, (4) production of three, one-half diameter lower head sections (at 2/3-scale) using PM-HIP, (5) assessment of heat-treatment sequence and schedules for application to the reactor subassemblies, (6) production of a 44% scale upper head using PM-HIP (under EPRI Advanced Nuclear Technologies in support of this project), (7) procurement of A508 powder to support major-component production, (8) assessment of vacuum annealing of powders prior to HIP, and (9) production of a major section of the RPV transition shell at 2/3-scale. In Q3 of 2019, fabrication of the lower assembly at Nuclear-AMRC will begin and the RPV transition sections will be completed using PM-HIP for the scale SMR RPV assembly.

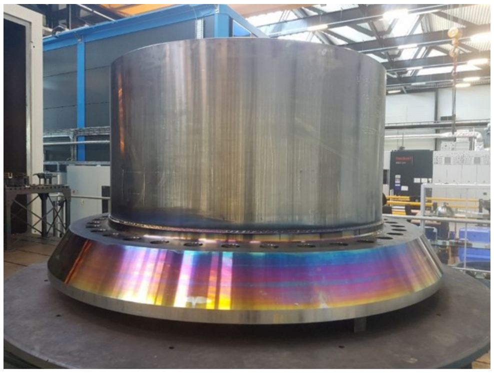

Figure 1. Lower-flange-shell mockup EBW of ~1.8 m dia. × 75 mm thick (note, mockup is upside down)

Figure 2. Forty-four percent scale A508 Cl1 Gr3 (1650 kg, 1270 mm) upper head with 27 penetrations, fabricated as one monolithic component (no welds)

SURFACE MODIFICATION AND CLADDING AWARDS

All-position Surface Cladding and Modification by FSAM

Zhili Feng, D. Alan Frederick, Xue Wang and Wei Tang, Oak Ridge National Laboratory

Greg Frederick and David Gandy, Electric Power Research Institute

Funding: $800,000 (10/01/2016-09/30/2019)

Description of Project: This research aims to develop a novel solid-state friction stir additive manufacturing (FSAM) process to improve erosion, corrosion, and wear resistance of nuclear internals and components. The research focuses on three activities: (1) the technical viability of FSAM and economic advantages on material combinations that are difficult or impossible with existing cladding or surface-overlay modification technologies involving melting and solidification, (2) fundamental understanding of and the technical basis to substantiate that FSAM would prevent defects caused by current fusion-cladding technologies, minimize service degradations, and reduce surface residual stresses for several targeted classes of advanced nuclear structural materials and austenitic stainless steels, and (3) prototypical surface-modified components for testing and evaluation to gain acceptance by the appropriate regulatory or standard-setting bodies and licensing for commercial nuclear plant deployment.

Impact and Value to Nuclear Applications: Cladding and surface modifications are extensively used in fabrication of nuclear reactor systems. Many technical issues exist in today's fusion-based cladding technologies, such as low productivity and high chemical-dilution ratio. More importantly, many alloys with superior corrosion resistance or other desirable properties are unsuited to fusion-based cladding due to solidification cracking and ductility-dip cracking (DDC), phenomena that are related to the nonequilibrium melting and solidification processes in fusion-cladding technologies. The FSAM process is fundamentally different. Its solid-state nature offers several key advantages, e.g., it (1) eases the metallurgical-incompatibility constraints in the use of new cladding materials, (2) minimizes the microstructural and performance degradations of high-performance structural materials, and (3) reduces the number of cladding layers for material/cost reduction and increase in productivity by its near zero dilution. The solid-phase FSAM would be expected to greatly improve cladding productivity with both high quality and reduced manufacturing cost in nuclear reactor component production and beyond.

Recent Results and Highlights: This project has successfully demonstrated the viability of cladding multimaterial combinations by the FSAM process. An example is given in which four layers of stainless steel 304 and Alloy 600 of total 3.4 mm thickness were deposited on the ASTM A516 Gr70 structural steel. A robust FSAM process model was also developed to correlate the interface temperature for bonding to the process conditions with adequate accuracy. This very fast process-development modeling tool allowed the team to quickly evaluate various combinations of process conditions in a matter of a few minutes so as to assist the optimization and refinement of the FSAM process for cladding. One application of the process model was to scale the tool size to increase the cladded area in one pass, improving cladding productivity. The tool size has been doubled to 1 inch diameter thus far. The goal is to increase the tool size to 2 inches in diameter to meet that target of a 20% overall increase in productivity, compared to typical arc-welding-based cladding processes.

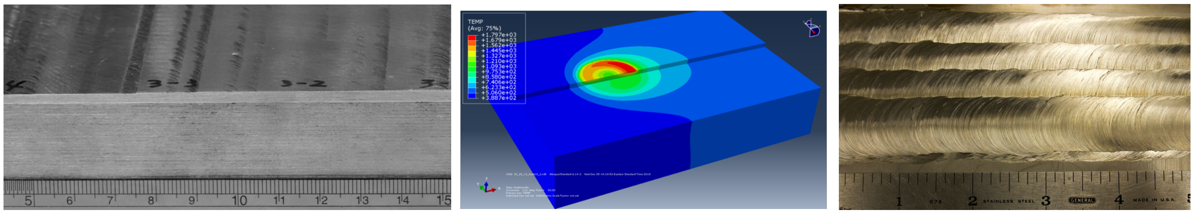

Figure 1. Left: a cross-section view of a multimaterial, multilayer FSAM build on a structural steel substrate. Middle: FSAM process model developed to assist with process refinement and optimization. Right: Process scaling. Successful FSAM cladding with 1-inch-diameter tool.

COMPLETED PROJECTS

Projects listed below have been completed, and summaries can be found in previous AMM Award Summaries available on the DOE-NE Website.

Welding & Joining

- Monitoring and Control of the Hybrid Laser-GMAW Process, Idaho National Laboratory, $800,000, 10/01/2012–09/30/2015
- Improving Weld Productivity and Quality by Intelligent Real-Time Closed-Loop Adaptive Process Control Through Integrated Optical Sensors, Oak Ridge National Laboratory, $800,000, 10/01/2014–06/30/2018

Surface Modification & Cladding

- Advanced Surface Plasma Nitriding for Development of Corrosion Resistant and Accident Tolerant Fuel Cladding, Texas A&M University, $800,000, 10/01/2015–09/30/2018

Modular Fabrication

- Modular Connection Technologies for Steel plate Composite Walls of Small Modular Reactors, Purdue University, $792,572, 08/15/2012–12/31/2015

Concrete Materials & Rebar

- Ultra-High-Performance Concrete and Advanced Manufacturing Methods for Modular Construction, University of Houston, $399,999, 01/15/2014–01/14/2016
- Self-Consolidating Concrete Construction for Modular Units, Georgia Institute of Technology, $400,000, 02/01/2014–04/30/2016
- Improvement of Design Codes to Account for Accident Thermal Effects on Seismic Performance, Purdue University, $800,000, 10/01/2014–01/31/2018
- Prefabricated High-Strength Rebar Systems with High-Performance Concrete for Accelerated Construction of Nuclear Concrete Structures, University of Notre Dame, $800,000, 10/01/2015–09/30/2018

Additive Manufacturing

- Laser Direct Manufacturing of Nuclear Power Components Using Radiation Tolerant Alloys, Lockheed Martin, $639,889, 10/01/2012–09/30/2015
- Innovative Manufacturing Process for Nuclear Power Plant Components via Powder Metallurgy- Hot Isostatic Pressing Electric Power Research Institute, $800,000, 10/01/2012–03/30/2016
- Development of Nuclear Quality Components Using Additive Manufacturing, RadiaBeam, $999,579, 07/28/2015–07/27/2017
- Additive Manufacturing of High-Strength Steel Components for SMRs Using a Superconducting Linearly Accelerated Electron Beam, Mainstream Engineering Corp., $150,000, 06/12/2017–03/11/2018 (SBIR Phase 1, Phase 2 underway)
- Environmental Cracking and Irradiation Resistant Stainless Steel by Additive Manufacturing, GE Global Research, $678,352, 10/01/2015–09/30/2017

Data Configuration Management

- Geo-Referenced, UAV-based 3D Surveying System for Precision Construction, Voxtel, Inc., Phase I: $150,000, 06/08/2015–03/07/2016 (Phase 2 underway)
- High Speed 3D Data for Configuration Management, TetraVue, $1,500,000, 07/28/2014–07/28/2016