NEET-ADVANCED METHODS FOR MANUFACTURING AWARD SUMMARIES

AMM
Advanced Methods for Manufacturing

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. Online, non-destructive testing, that can provide real-time, or near real-time, feedback on the quality of a weld, would improve the productivity in both the shop and the field.

2. **Additive Manufacturing.** This process, compared to 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.

3. **Modular Fabrication.** This concept will move new nuclear reactor builds away from "piece built" fabrication and construction techniques. The modules are 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 the conventional "stick builds."

5. **Data Configuration Management.** Complex civil and mechanical designs need to maintain their design configuration for the duration of construction and the operational life of the facility. Digital gathering of data and multi-dimensional 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, causing 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 technology innovations through competitive solicitations issued annually that are open to industry, academia and national laboratories. The program seeks proposals through the annual Consolidated Innovative Nuclear Research (CINR) Funding Opportunity Announcement (FOA). For more information on this solicitation, 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, visit www.science.energy.gov/sbir. Another opportunity for AMM projects is through the new "U.S. Industry Opportunities for Advanced Nuclear Technology Development" FOA, which is available at https://www.id.energy.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) in the areas of seismic isolation system and laser-arc hybrid welding. This projects were completed in 2014.

In FY 2012, four projects (totaling $3,032,461) were awarded through the CINR solicitation in the areas of welding and additive manufacturing. This projects were completed in 2015.

In FY 2013, two awards (totaling $737,374) were issued through the CINR solicitation in the area high performance and self-consolidating concrete. This projects were completed in 2016.

In FY 2014, three projects (totaling $2,400,000) were selected through the CINR. The first was awarded to the University of Houston for the further development of its 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 the Small Business Innovation Research (SBIR) solicitation, for a Phase II grant (totaling $1,500,000). TetraVue, Inc., from San Marcos, California, is researching 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 the irradiation resistance and stress corrosion cracking resistance on in-core components manufactured by direct metal laser melting (DMLM), and to develop novel methods for onsite fabrication of continuous large-scale structures, respectively. One award was given to Texas Agricultural and Mechanical (A&M) University to develop an advanced surface plasma nitriding technique. The University of Notre Dame is investigating 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, is exploring data configuration management systems. Both RadiaBeam and Voxtel received Phase II SBIR awards of $1,000,000 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 nano-structuring. 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 will test 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 DOE-funded research and development of a PM-HIP process.

In a program funded in FY 2017 at $1,000,000, the University of Wisconsin will investigate cold spray additive manufacturing of oxide dispersion strengthened (ODS) steel cladding tubes and as a surface modification technology. NovaTech received SBIR funding to use three-dimensional (3D) printing to produce hold down springs and bottom nozzles for BWR fuel assemblies. In another SBIR project, Mainstream Engineering is using its Electron Beam-Enabled Advanced Manufacturing (EBEAM) facility to explore manufacturing SMR components made of 316L stainless steel.

As part of the U.S. Industry Opportunities for Advanced Nuclear Technology Development initiative, DOE-NE has made two awards in FY 2018. BWXT Nuclear Energy, Inc., of Lynchburg, Virginia, received an award to pursue the establishment of an integrated advanced manufacturing and data science driven paradigm for advanced reactor systems. In collaboration with ORNL, this project will develop the ability to implement additive materials manufacturing to the fabrication process for nuclear components and subcomponents that will yield acceptable material structure and strength. DOE is providing $5,000,000 in cost sharing for the $9,815,000 project. In addition, Holtec International, Camden, New Jersey, will receive $6,314,612 in DOE cost share for a $12,629,224 project to advance and commercialize Hybrid Laser Arc Welding for nuclear vessel fabrication, including small modular reactors.

Since 2011, the AMM program has awarded more than $30 million for initiatives to improve the cost and schedule for new nuclear power plants, and to fabricate components more economically and reliably. 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. The following sections show that the developments and innovations continue to surpass the expectations of the NEET AMM program.

The following pages provide status reports and lessons learned from current ongoing projects that are sponsored under the Advanced Methods for Manufacturing program. These projects involve:

- Welding and joining
- Additive manufacturing
- Modular fabrication
- Concrete materials and rebar
- Surface modification and cladding.

WELDING AND JOINING AWARDS

Improving Weld Productivity and Quality by means of Intelligent Real-Time Close-Looped Adaptive Welding Process Control through Integrated Optical Sensors

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Description of Project: The increasing need for improving weld quality and productivity requires advanced welding monitoring and control technologies. In our research, a multi-optical sensing approach is under development to maximize the effectiveness of reliable welding process control to eliminate the formation of weld defects. The sensing system mainly consists of a single or stereo visible (VIS) camera system, an infrared (IR) camera, a weld pool surface measurement sensor and the necessary auxiliary illumination sources and filters. The sensing system is capable of measuring, in real time, weld thermal-mechanical response (distortion, strain and stress) adjacent to the fusion line and dynamic changes of the weld pool.

Impact and Value to Nuclear Applications: The existing weld quality inspection for manufacturing nuclear reactor structures mostly relies on post-weld NDE techniques. If defects are identified, the reworking (or scrapping if beyond repair) of manufactured structures are costly and time-consuming for the thick-section reactor structures. The multi-sensing system monitors and controls the weld quality in real time. By drastically reducing weld defects, which is the rework required for defect mitigation, the online system can significantly decrease the component fabrication cost, accelerate the deployment schedule, and increase the integrity and reliability in a variety of nuclear reactor designs and components.

Recent results and highlights: In the first two years, the initial algorithm development was mainly focused on bead-bead-plate autogenous welding conditions. Optical signals were successfully extracted and correlated to weld quality (weld penetration, lack-of-fusion, strain/stress evolution, etc.). In this year, the R&D work was focused on thick section of weldment, simulative to the real-world weld components. Multiple weld passes were required to fill the weld groove. The capability of penetration control was demonstrated on the first weld pass (root weld) as shown in Figure 1. The initial welding condition (without adaptive control enabled) was insufficient to produce full-penetration weld. With control enabled, the system automatically adjusted welding parameters and full-penetration welds were achieved. In addition, the system was able to detect and correct lack-of-fusion defect as illustrated in Figure 2. When the control was off, side-wall lack-of-fusion was detected. When adaptive control was turned on, the defect was minimized.
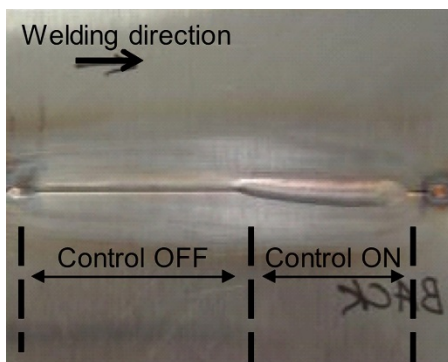

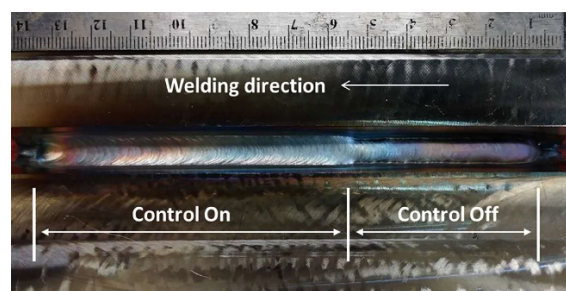*Figure 1. Control to make full-penetration welds.*

Figure 2. Control to minimize lack-of-fusion defect.

ADDITIVE MANUFACTURING AWARDS

Environmental Cracking and Irradiation Resistant Stainless Steel by Additive Manufacturing

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Fran Bolger and Myles Connor, GE-Hitachi Nuclear Energy;

Gary S. Was, Miao Song and Mi Wang, University of Michigan;

Fred List III, Oak Ridge National Laboratory;

Project Summary: This is the first study in the world that delivers a comprehensive understanding of the nuclear related properties of additively manufactured (AM) austenitic stainless steel (SS) and its process-structure-property relationship for nuclear applications. The research contributes to development of nuclear specifications for both non-critical and critical applications. Based on the findings, GE has demonstrated the technology, completed the cost analysis for its commercialization, and communicated with nuclear industry stakeholders.

Material Development Summary: A good understanding of nuclear-related material properties and the relationship among process, microstructure, and properties are the keys for the nuclear industry to adopt a new technology. The project has made significant progress in the following areas:

Figure 1. IASCC susceptibility of 316L after proton and heavy ion irradiation
(SR = Stress Relieved, PD = tensile load applied in printed direction)

IASCC susceptibility of 316L after proton and heavy ion irradiation

1) Powder development, microstructure control and process optimization for AM 316L stainless steel, AM Alloy 800, and the modification of AMSS.

2) High-resolution characterization to understand the hierarchy of the AM stainless steel, such as grain/dendrite structure, strain distribution, boundary structure, segregation, precipitation, etc.

3) Tensile properties of AM SS are similar or better than its wrought counterpart.

4) Comprehensive stress corrosion cracking growth study of various heats was performed, including the effects of microstructure, heat treatment, stress intensity factor, cold work, crack orientation, oxidizing versus reducing conditions, and porosity. High-temperature post-manufacturing treatment is required for nuclear applications. Hot Isostatic Pressing (HIP) may not be needed if the as-built part shows good density.

5) Comprehensive corrosion fatigue study of AM 316L stainless steel. AM 316L SS shows similar corrosion fatigue response to its conventional forged material.

6) Comprehensive study of proton and heavy ion irradiation effect and irradiation assisted stress corrosion cracking (IASCC) was conducted on AM materials. Based on the results, the HIP AM 316L SS shows better irradiation tolerance and IASCC resistance than both stress-relieved AM 316L SS and wrought 316L SS (see Figure 1).

Nuclear Product Demonstration Summary: The additive manufacturing design and fabrication process was executed with a rigorous nuclear quality assurance (QA) oversight program to produce nuclear fuel debris filters. These parts were subject to material testing and have the fabrication pedigree to be considered for in-reactor use. The GE Nuclear component inspection and qualification program was adapted and executed for the first time on AM parts. This included supplementing the standard GE Nuclear inspection processes with Computerized Tomography (CT) and Blue Light scanning to better characterize additive manufacturing tolerances. The additive debris filter meets all design criteria.

The results were consolidated to form a baseline for GE Nuclear internal AM material specification. The roadmap for nuclear specification and regulatory requirements was discussed with the U.S. NRC.

The cost per part and capital investment requirements for a production scale facility were determined. The cost per part for the fuel debris filter was estimated to be higher than the conventional manufacturing process, but the performance of the additive debris removal was sufficient such that it would still be profitable.
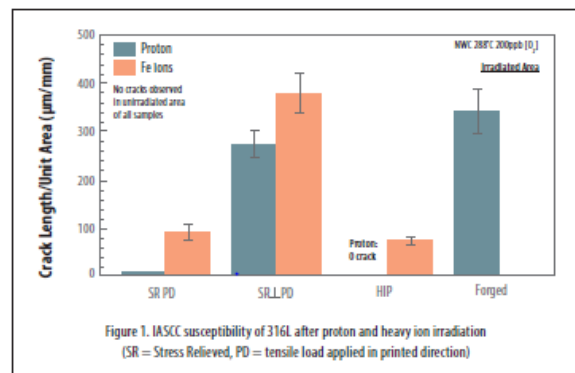
Integrated Computational Materials Engineering and *In-situ* Process Monitoring for Rapid Qualification of Components Made by Laser-Based Powder Bed Additive Manufacturing Processes for Nuclear Applications

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D. Poole and T. Hare (Rolls-Royce);

W. Cleary and C. Armstrong (Westinghouse);

Description of Project: Nuclear power plant equipment manufacturers have realized the potential to deploy additive manufacturing (AM) methods to produce reactor internal components due to its unique capability to generate complex geometries rapidly with improved performance, while reducing the cost and time to market. At the same time, Code and regulatory bodies are skeptical about adopting these components for real-life service due to the scatter in metallurgical and mechanical properties emanating from machine specific and process variations. Although current efforts to develop qualification standards (e.g., ASTM Committee F42 on Additive Manufacturing) are based on fabrication/ testing of coupons, there is no clear, concise methodology for component process-based certification. Electric Power Research Institute (EPRI) collaborators are developing a rapid component level qualification method that combines AM with high fidelity process optimization and control. Specifically, the overall methodology combines process sensing, control, nondestructive inspection, and integrated computational materials engineering (ICME).

Three 316L stainless steel tee-shaped pipe sections were produced with structural defects implanted into them for characterization.

Impact and Value to Nuclear Applications: An innovative qualification strategy for complex parts produced by laser powder bed (LPB-AM) will be developed and demonstrated by leveraging relevant technology from recent welding developments, as well as emerging process analytics, high-performance computation models, in-situ monitoring and big-data mining. LPB-AM processes have the potential to develop an entirely new field for manufacturing nuclear internal components. Coupling the technology with ICME and in-situ process monitoring can provide industry with a qualification strategy/approach to assure nuclear quality can be met.
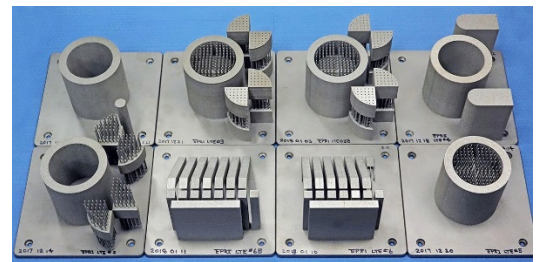
Six different pipe coupons were produced by LBP-AM to assess changes in microstructure and mechanical properties associated with moving from a thin-to-thick region and hold time/heat load for each. Additionally, two conventional X, Y, and 45 degree coupons were performed to assess heat loading conditions.

Recent Results and Highlights: The jointly funded project was initiated in in the fourth quarter of 2016. Much of the effort in 2017 was dedicated to: (1) establishing in-situ monitoring capabilities, (2) completing two components produced by AM, including a bottom fuel nozzle (Westinghouse), and tee-piece (Rolls Royce) from two different alloys: 316L stainless steel and Alloy 718, and (3) understanding how LPB-AM microstructure and properties are affected by changes in the geometry of a component build. Thermal imaging was used as an in-situ monitoring technique to assess localized point defects in multiple cube buildups performed in the project. Data generated from the IR assessment suggested defects <200 µm would be difficult to detect. Additionally, understanding of the microstructure/ mechanical properties is to be assessed through application of individual thin pipe coupons that included a thick plate section in the center. Different layer hold time and heat loads were applied and the components are now being characterized by the investigators in terms of tensile, toughness, hardness, and microstructure.

Enhancing Irradiation Tolerance of Steels via Nano-structuring by Innovative Manufacturing Techniques

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James I. Cole, Yongfeng Zhang, Isabella J. van Rooyen, Idaho National Laboratory;

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 a feasibility assessment of applications of two low-cost advanced manufacturing techniques (ECAP and HPT) in fabricating materials with improved performance for current and advanced reactors, with an established/enhanced understanding of the irradiation effects in UFG and NC F/M steels. The application of low-cost advanced manufacturing techniques in fabricating currently used materials in light water reactors (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 impacts on nuclear energy research and development.

Recent Results and Highlights: Pre-irradiation characterization was performed on bulk nanostructured austenitic steels (304 and 316 steels) and F/M steels (Grade 91 and Kanthal D steels) manufactured by ECAP and HPT. Results indicated that the UFG steels manufactured by HPT and ECAP possess significantly improved hardness/strength compared to their conventionally manufactured coarse-grained counterparts. Grain size of HPT samples is smaller (~150 nm) than ECAP samples (~400 nm). ECAP samples exhibit texture while HPT samples do not. Second-phase particles identified in each sample include: $M_{23}C_6$ and M_3C in ECAP 304; Ti_2C particles, Ni-Mn-Si particles, Cr particles, and Cu-rich precipitates in HPT 304; no second-phase particles found so far in ECAP 316; cementite and Cr-rich $M_{23}C_6$ in HPT 316; Mo-rich M_2C, Cr-rich $M_{23}C_6$ and Nb-rich MX phase in HPT Grade 91. All the ECAP and HPT steels are thermally stable at least up to 500°C, and many of them are stable up to 600 °C. Neutron irradiation design was completed. Samples to be neutron irradiated have been machined into specific geometry and dimensions. They are going into the Advanced Test Reactor at Idaho National Laboratory in June 2018.
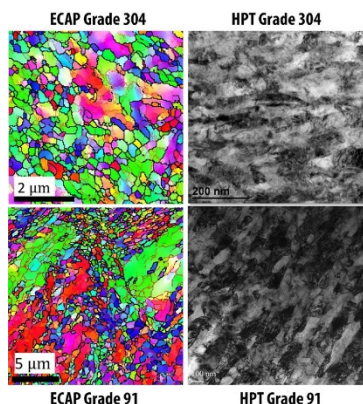
Electron backscatter diffraction orientation maps and transmission electron microscopy images showing the microstructure of steels manufactured by ECAP or HPT.
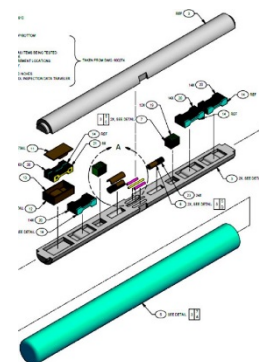
Schematic of a neutron irradiation capsule.

Additive Manufacturing of High Strength Steel Components for SMRs using a Superconducting Linearly Accelerated Electron Beam

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Summary: The adoption of small modular reactors (SMRs) is expected to lead to greater flexibility in power generation, lower energy costs, and reduced development schedules for power plants. Additive manufacturing is predicted to reduce the deployment times and SMR costs by up to six months and 20 percent, respectively. Additive manufacturing produces parts rapidly, with less raw material, and with less waste compared to traditional machining. However, comparable physical properties of these additively manufactured components with traditionally fabricated counterparts are not yet achievable.

Mainstream Engineering introduced a new dimension to additive manufacturing through its Electron Beam-Enabled Advanced Manufacturing (EBEAM) facility. This system produces an electron beam with 30-times-higher energy leading to far-from-equilibrium material processing. This capability can impart additional functionality through microstructure refinement that can include increased strength, increased hardness, and improved wear resistance.

During Phase I, we studied the unique microstructure produced during high-energy, electron beam additive manufacturing of steel from powder. We evaluated the material properties of additively manufactured sample coupons of 316L stainless steel and compared to cast 316L. We worked closely with a leading SMR developer to identify and target specific components for additively manufacturing in Phase II. Overall, we believe the unique microstructure in the EBEAM additively manufactured components could open new potential in multi-functionality and increased strength in additively manufactured components.
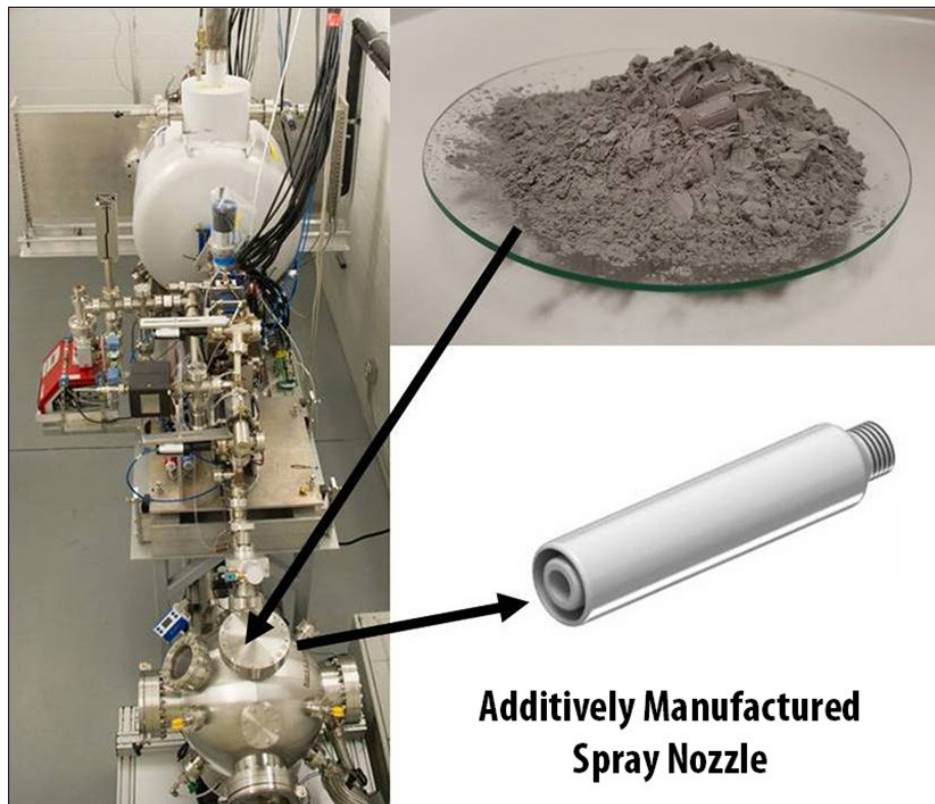
High-energy, high-power electron beam-enabled additive manufacturing of steel components for SMRs.

Irradiation Performance Testing of Specimens Produced by Commercially Available Additive Manufacturing Techniques

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Description of Project: The project will collect irradiation performance data for stainless steel and Inconel specimens produced using commercially available additive manufacturing techniques. Test specimens have been harvested from billets produced by a set of currently available additive manufacturing techniques. The Colorado School of Mines will conduct pre-irradiation thermo-mechanical testing (tensile strength, yield strength, elastic modulus, ductility, thermal conductivity and thermal diffusivity) and micro-structural characterization of the un-irradiated specimens. The Advanced Test Reactor (ATR) is currently irradiating a second set of specimens at typical light water reactor temperatures. A comparison of the physical properties and microstructure of the irradiated specimens to those of the as-fabricated and thermally-aged 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 additive manufacturing 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 additive manufacturing 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.

Recent Results and Highlights: The ATR irradiation will be complete by the end of December. Post-irradiation thermo-mechanical testing and micro-structural characterization of the irradiated specimens will be conducted at Nuclear Science User Facility (NSUF) post-irradiation examination facilities. The Colorado School of Mines is currently conducting characterization and testing of the un-irradiated specimens.

Schematic of a neutron irradiation capsule.

Loading the tensile bar specimens into the ATR sample capsules.

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;

Stuart Maloy, Los Alamos National Laboratory;

*Dr. Patrick Grant, Oxford University;*

Description of Project: Cold spray additive manufacturing 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. Since cold spray is a solid-state process, no melting of the powder particles occurs making it ideal for the fabrication of ODS steel cladding tubes, where melting processes will lead to upward stratification of oxide nanoparticles.

Impact and Value to Nuclear Applications: The project introduces a low-temperature, solid-state, high-deposition rate process for the rapid manufacturing of components to the nuclear industry, while significantly adding to the component's value in terms of lower cost and improved properties. In the case of ODS steel cladding, the cold spray approach obviates the need for multiple extrusion and annealing steps presently used for the manufacturing of such 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 also will enable the near-term deployment of materials in nuclear reactors, which are presently either not cost-competitive to manufacture or are restricted by scientific barriers in conventional manufacturing processes.

Recent Results and Highlights: This project has started developing the cold spray process. A gas atomized non-oxygen containing 14YWT powder was cold sprayed on a rotating cylindrical aluminum-alloy mandrel using pressurized N2 gas. The process produced an approximately one-millimeter thick, dense 14YWT layer on the aluminum-alloy tube. After surface polishing to obtain desired cladding thickness and surface roughness, the mandrel was ionized and dissolved using an aqueous alkaline solution to leave behind a free-standing ODS tube (Figure 1). The as-fabricated cladding tube was annealed at 1000°C for one hour to recrystallize and increase ductility of the cladding (Figure 2). These initial studies have demonstrated the concept's feasibility. Ongoing work includes optimizing the cold spray process for a new oxygen-containing ODS powder, followed by high-temperature post-deposition heat treatments to precipitate oxide nanoclusters of yttrium and titanium that impart high-temperature strength and radiation damage resistance to this alloy. Separately, we are investigating mechanical alloying of atomized powders to produce precursor powders for the cold spray process.
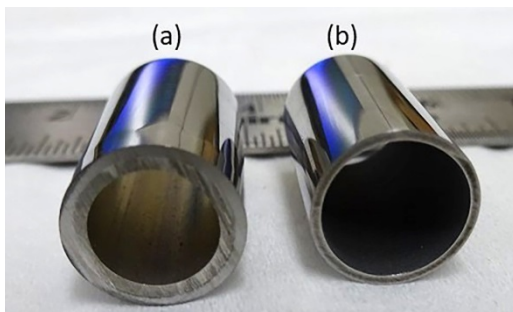
Loading the tensile bar specimens into the ATR sample capsules.
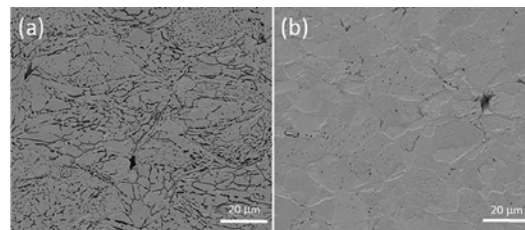
Schematic of a neutron irradiation capsule.

MODULAR FABRICATION AWARDS

Small Modular Reactor (SMR) Reactor Pressure Vessel Manufacturing and Fabrication Technology Development

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

Funding: $2,500,000 (10/01/2017–9/30/21)

Description of Project: Many of the same manufacturing and fabrication technologies that were employed for light water reactor plants built 30–50 years ago are also being employed today to build advanced light water reactors (ALWR). Manufacturing technologies have not changed dramatically for the nuclear industry even though higher quality production processes are available, which could be used to significantly reduce overall component manufacturing and fabrication costs. New manufacturing and fabrication technologies that can accelerate production and reduce costs are vital for the next generation of plants, SMRs and Advanced GEN IV plants, to assure they can be competitive in today's and tomorrow's markets. The project has been 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).

Electron beam welding parameters are being established for SA355 and A508 components to determine optimum welding conditions for 110-mm-thick component welds, which will be produced throughout the project. The three photos show welds performed at different energy inputs.

Impact and Value to Nuclear Applications: Through use of technologies including: electron beam welding (EBW), powder metallurgy-hot isostatic pressing (PM-HIP), diode laser cladding, and advanced machining, Electric Power Research Institute (EPRI) and the United Kingdom's Nuclear-Advanced Manufacturing Research Centre (Nuclear-AMRC) will seek to demonstrate that critical sections of an SMR reactor can be manufactured and fabricated in a timeframe of less than 12 months and 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 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: During 2017, considerable progress was made in the SMR manufacturing and fabrication project including: (1) securing trial test RPV materials/components for conducting EB welding development and mockup demonstrations, (2) completed detailed project scheduling for the project, (3) began development of EB welding parameters for thick section components, (4) established the work package for diode laser cladding (work to begin in early 2018), (5) completed capsule (can) development for one-half of the 2/3rds scale lower RPV head, (6) secured A508 powders for completion of the lower head sections, (7) established A508 powder/HIP properties and consistency, (8) established a mechanical/microstructural test matrix to support ASME BPV Code efforts in the future, (9) completed assessment of heat treatment criteria for the project, and (10) secured four major SA508 Grade 3 forgings for the project. In Q2-2018, we plan to begin assembly of trial mockup components at Nuclear AMRC and to complete the lower head sections using PM-HIP for the 2/3rds SMR vessel assembly.
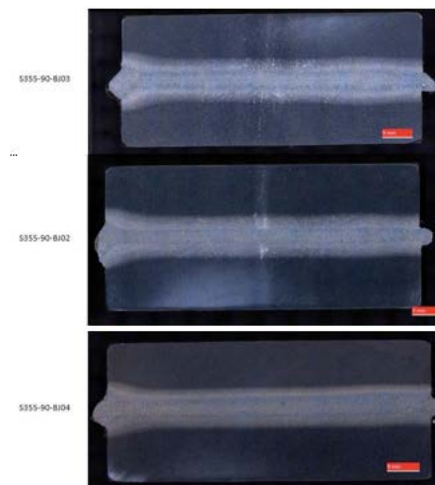
A 70-inch (1780mm) one-half diameter capsule (can) was produced in 2017 for the 2/3rds scale lower reactor head, which is to be filled with powder and HIP'ed in 2018.

CONCRETE MATERIALS AND REBAR AWARDS

Prefabricated High-Strength Rebar Systems with High-Performance Concrete for Accelerated Construction of Nuclear Concrete Structures

Y. C. Kurama and A. P. Thrall, University of Notre Dame;
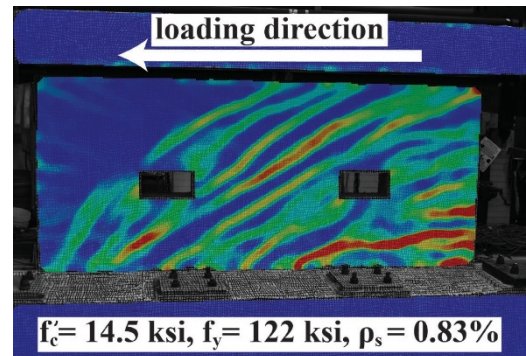
S. E. Sanborn, Sandia National Laboratories;
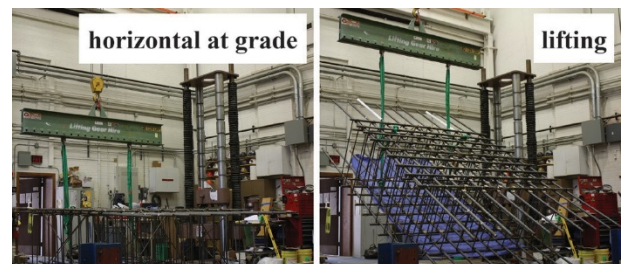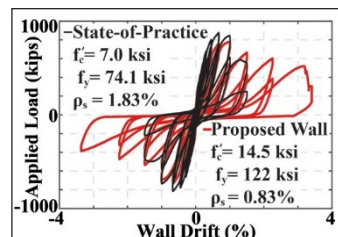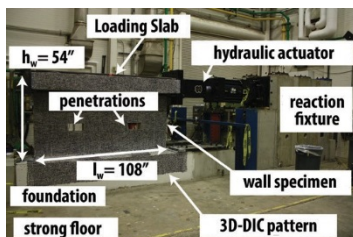
M. Van Liew, AECOM;

Description of Project: This project aims to reduce field construction times and fabrication costs of reinforced concrete (RC) nuclear safety-related structures through the use of: (1) high-strength steel deformed reinforcing bars (rebar); (2) prefabricated rebar assemblies with headed anchorages; and (3) high-strength concrete. The focus is to fill a major knowledge gap on the effectiveness, code conformity, and viability of the use of existing high-strength materials in nuclear structures, especially in stocky shear walls.

Impact and Value to Nuclear Applications: The envisioned advances will result in generalized outcomes with reduced volumes/complexities of rebar (fewer/smaller bars and bar layers), which will reduce material/shipping/fabrication costs, facilitate concrete placement and consolidation, and improve construction quality and ease of inspection.

Recent Results and Highlights: The project tested four deep cantilever beams (representing slices from a prototype shear wall) under monotonic lateral loading. The specimen utilizing both high-strength steel and high-strength concrete resulted in the greatest lateral strength and deformation capacity, demonstrating the benefits of combining these materials. Furthermore, the following two shear wall specimens were tested under reversed-cyclic lateral loads (Figure 1): (1) a state-of-practice wall with normal-strength materials; and (2) a proposed wall with high-strength materials and reduced reinforcement ratio. The wall with high-strength materials used approximately 55% less rebar than the state-of-practice wall, and yet, was able to achieve 91% of the peak strength, 100% of the initial stiffness, and 74% of the post-cracking stiffness, with also greater deformation capacity. The concrete surface deformations were measured using three-dimensional digital image correlation (3D-DIC), providing detailed information on damage progression and deformation modes (Figure 2). Ongoing work is focused on testing of a third shear wall specimen (with high strength materials) and numerical modeling. Additionally, prefabricated rebar assemblies were investigated via an industry survey and laboratory evaluation. Full-scale wall rebar mats and cages were constructed to determine

Maximum principal (tension) strains at peak strength.

changes in rebar spacing when lifting a horizontally prefabricated assembly to vertical (Figure 3). The largest spacing changes were measured (using 3D-DIC) in the horizontal bars involved in lifting. Use of headed transverse rebar, different number of rebar layers, or different wall thicknesses had no significant effect on the spacing changes. The survey and experiments indicate that nuclear structures are excellent candidates for rebar prefabrication.

Wall specimen in laboratory (left) and lateral load versus drift behavior of two walls with different rebar yield strength, fy, concrete compression strength, f'c, and rebar ratio, ρs (right).

Prefabricated rebar assembly lift tests.

Improvement of Design Codes to Account for Accidental Thermal Effects on Seismic Performance

*A. H. Varma, Purdue University, West Lafayette, IN 47906;*

Description of project: The Fukushima nuclear accident of 2011 has highlighted the importance of designing safety-related nuclear facilities for accident thermal scenarios combined with design basis and beyond design basis shaking. While the probability of both events occurring simultaneously is low, severe environmental conditions may trigger accident thermal loading. Furthermore subsequent aftershocks, potentially as intense as the main shock, may occur during the accident thermal event. Current design codes and standards in the United States and abroad provide little-to-no guidance for including the effects of accident thermal loading on seismic behavior (stiffness, strength, ductility or reserve margin) of structures. The overall goal of this research project is to develop knowledge-based design guidelines for safety related nuclear facilities subjected to combined accident thermal conditions and seismic loading.

Impact and value to nuclear applications: The results from the experimental and analytical investigations will be used to develop design guidelines and recommendations for SC and RC walls subjected to combined accident thermal loading and earthquake shaking, including design basis (SSE) and beyond design basis shaking. This knowledge will expedite future design and licensing through validated recommendations for analysis and design, suitable for consideration by committees of ACI 349 and AISC N690 (design and detailing) and ASCE Standards 4 and 43 (analysis and design).

Recent Results and Highlights: Experimental results indicate that typical magnitudes and durations of thermal loads do not significantly reduce the strength of SC and RC wall structures. The strength for thermal load combinations can be determined using existing code provisions for ambient temperatures. For example, Figure 1 shows the load-displacement response for SC wall specimen subjected to combined thermal and lateral loading. The strength of the specimen is 30% higher than the nominal strength per AISC N690s1. However, the stiffness of SC and RC wall structures reduces considerably as thermal loads are applied. The reduction in stiffness is attributed to extensive concrete cracking due to non-linear thermal gradients through the thickness of the specimens. The extent of reduction in the stiffness depends on the magnitude and duration of accident temperatures (higher stiffness reduction is observed for surface temperatures of 450°F in comparison to 300°F). For SC walls, stiffness reduction of up to 40% was observed (the stiffness degradation for SC wall specimen due to thermal loads can be seen in Figure 2). For RC walls, the extent of stiffness reduction is due to additional concrete cracking; and once the concrete is cracked in flexure or shear, thermal loads do not result in any additional cracking.
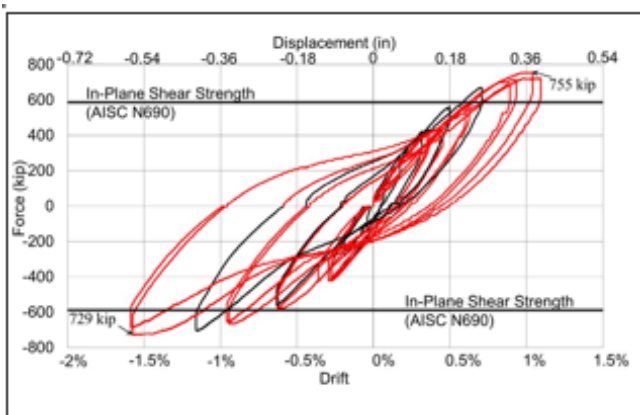
Load-displacement response of SC wall specimen.
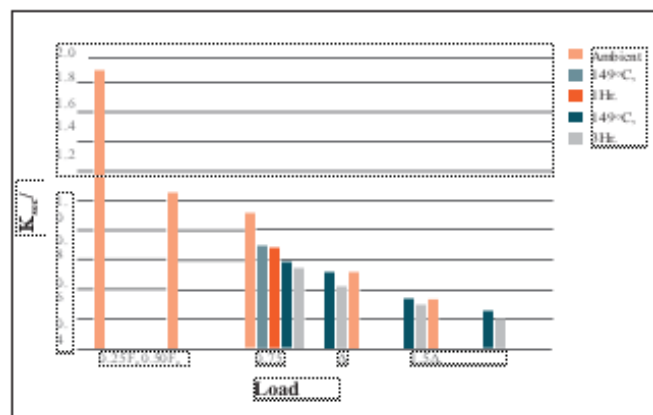
Stiffness degradation for SC wall specimen.

SURFACE MODIFICATION AND CLADDING AWARDS

Advanced Surface Plasma Nitriding for Development of Corrosion Resistant and Accident Tolerant Fuel Cladding
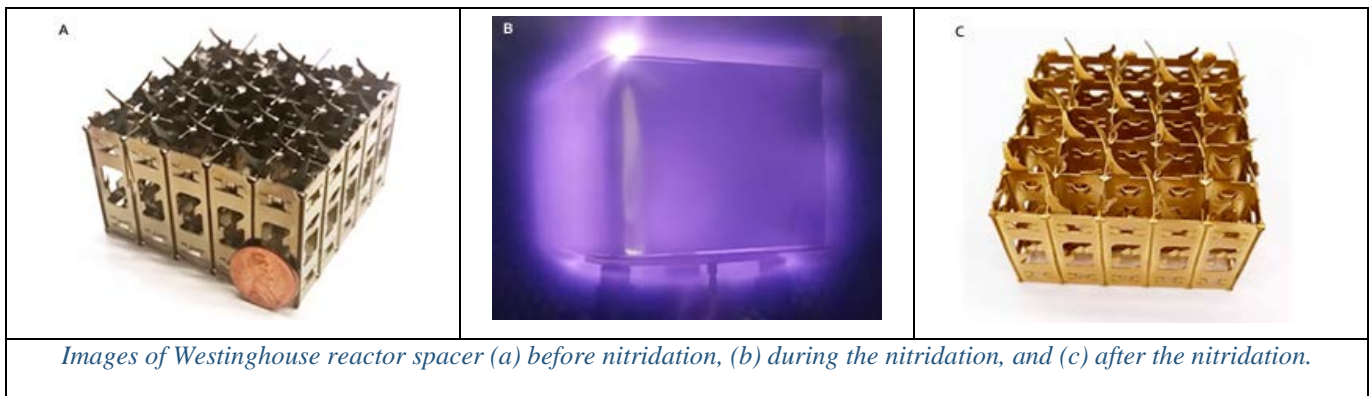
Lin Shao[1], Don Lucca[2], Michael Short[3;]

[1]Texas A&M University, [2]Oklahoma State University, and [3]Massachusetts Institute of Technology;

Description of Project: This project aims to develop a hollow cathode plasma nitriding technique for surface modification of fuel cladding materials, driven by the need to increase corrosion resistance and accident tolerance. Starting with alloys of Department of Energy (DOE) interest, the team applies an advanced surface plasma nitriding technique to produce a nitride layer on the surface for better structural integrity and compatibility with both coolants and nuclear fuels. The project involves Texas A&M University for nitridation experiments, ion irradiation, and structural characterization; Oklahoma State University for mechanical property testing; and Massachusetts Institute of Technology for corrosion and oxidation testing.

Impact and Value to Nuclear Applications: In reactor harsh environments involving high stress, corrosion, and irradiation damage, fuel cladding materials experience severe structural changes and degradation. These changes impact not only the lifespan of the cladding but also reactor safety and reliability. Although numerous studies have shown that a surface nitride layer can increase hardness, wear resistance, oxidation resistance, and corrosion resistance, there has not been a systematic investigation pertaining to nitriding effects on fuel cladding materials, particularly when neutron damage and fuel cladding interactions must be considered. Furthermore, existing plasma nitriding techniques are not able to uniformly modify complicated structures.

Recent Results and Highlights: The team has identified all major parameters to achieve uniform nitride layers on various alloys including 316L, HT-9, and Zircaloy 4. Diffusion kinetics, nitride phases, and mechanical property changes have been studied. Through a combination of transmission electron microscopy for structural characterization, cross-sectional indentation for hardness changes, cross-sectional second ion mass spectrometry for nitrogen profiling, cross-sectional Raman analysis for nitride layer formation, we obtained a comprehensive understanding of nitridation effects on materials' structural and property changes, and the correlation between the two. The study extended to reactor components of complicated geometry to demonstrate the suitability of the technique to realistic applications. The second year has focused primarily on corrosion resistance testing in BWR and PWR-like coolants. The studies have shown that nitridation can significantly increase corrosion resistance.

Images of Westinghouse reactor spacer (a) before nitridation, (b) during the nitridation, and (c) after the nitridation.

All-Position Surface Cladding and Modification by FSAM

Zhili Feng and Wei Tang, Oak Ridge National Laboratory, Oak Ridge, TN 37831;

*Greg Frederick and David Gandy, Electric Power Research Institute, Charlotte, NC, 28262;*

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 will focus on three activities: (1) the technical viability of FSAM and economic advantages of material combinations that are difficult or impossible with existing cladding or surface overlay modification technologies involving melting and solidification, (2) the fundamental understanding 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 or high chemical dilution ratio. More importantly, many alloys with superior corrosion resistance and/or other properties are difficult for fusion-based cladding due to solidification cracking and ductility-dip cracking (DDC) that are related to the non-equilibrium melting and solidification processes in fusion cladding technologies. The FSAM process is fundamentally different. Its solid-state nature offers several key advantages: (1) ease the metallurgical incompatibility constraints in use of new cladding materials, (2) minimize the microstructure and performance degradations of the high performance structural materials, and (3) near zero dilution reduces the number of cladding layers for material/cost reduction and increase in productivity. The solid-phase FSAM would be expected to greatly improve cladding productivity with high quality and reduced manufacturing cost in nuclear reactor component production and beyond.

Recent Results and Highlights: So far, we have successfully demonstrated the feasibility of friction stir cladding of several different materials onto a structural steel substrate. The feasibility of additively building layers of different materials on top of each other has also been successfully demonstrated. Build quality was characterized by means of C-scan ultrasonic non-destructive evaluation, interface microstructure analysis and destructive testing. High-quality solid-state bonding has been achieved so far, as shown in Figure 1 below.
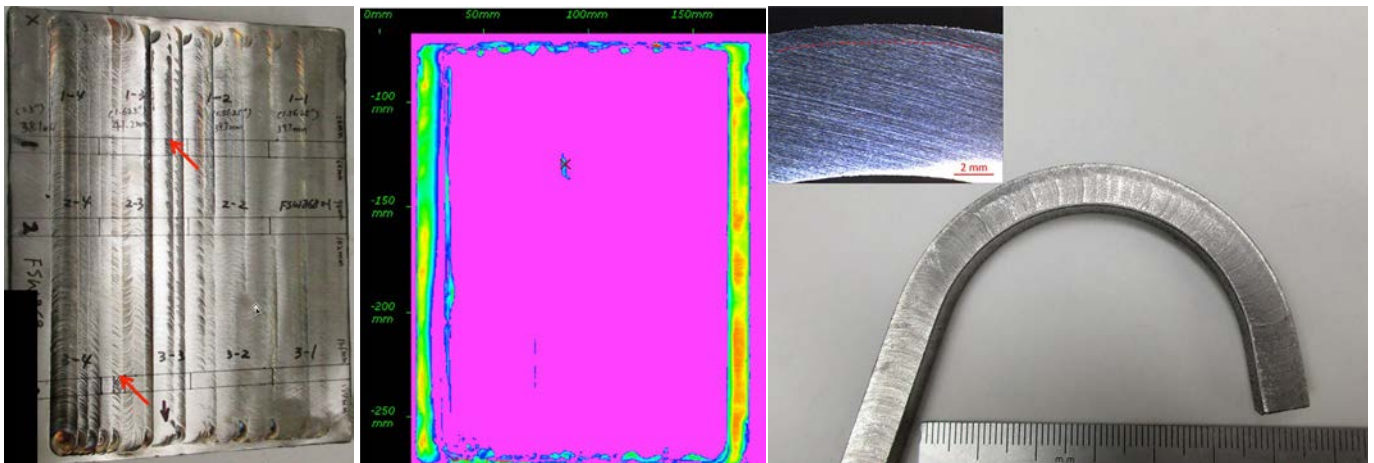
Left: a 6-in. x 4-in. FSAM build with multiple layer materials on a structure steel substrate. Middle: C-scan ultrasonic inspection showing quality bond by FSAM. Right: side bend test showing quality bond.

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

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

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

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 II underway)

- High Speed 3D Data for Configuration Management, TetraVue, $1,500,000, 07/28/2014–07/28/2016

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