OFFICE OF NUCLEAR ENERGY

NEET-ADVANCED METHODS FOR MANUFACTURING AWARD SUMMARIES

AMM

Advanced Methods for Manufacturing

NUCLEAR ENERGY ENABLING TECHNOLOGIES – ADVANCED METHODS FOR MANUFACTURING

JUNE 2017

15-50170-R2

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:

- To reduce the cost and schedule for new nuclear plant construction
- To 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. On-line, non-destructive 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, 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. 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 steelform assemblies will also help to move new builds away from the conventional "stick builds".
5. *Data Configuration Management.* Complex civil and mechanical designs, and the systems they make up, 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. 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 technology innovations through competitive solicitations issued annually that are open to industry, academia and national laboratories. The program seeks to develop manufacturing and fabrication innovation, assembly processes, and materials innovation that support the "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 have the 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, 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. Lastly, an award was given for the monitoring and control of the hybrid laser-gas metal arc welding process to the Idaho National Laboratory.

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 ultra-high 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 the 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 the Small Business Innovation Research (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 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 on-site fabrication of continuous large-scale structures, respectively. One award was given to Texas Agricultural & Mechanical (A&M) University to develop an advanced surface plasma nitriding technique. The University of Notre Dame will 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 FY2016, 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 are 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 FY2017. The project builds on EPRI's earlier DOE-funded research and development of a PM-HIP process.

Since 2011, the AMM program has awarded a total of $20,420,434 for 24 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.

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

Jian Chen, Roger Miller, Zhili Feng, Oak Ridge National Laboratory
Yu-Ming Zhang, University of Kentucky
Robert Dana Couch, Electric Power Research Institute
Funding: $800,000 (10/01/2014 – 9/30/2017)

Description of Project: The increasing need for improving weld quality and productivity requires advanced weld 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 (Figure 1) 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.

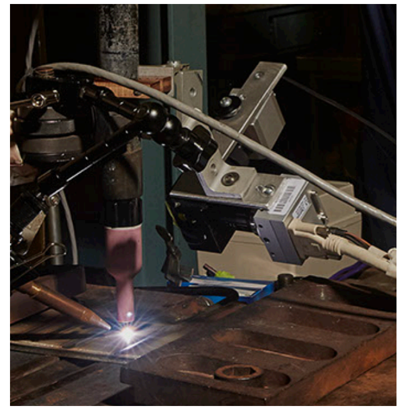

Figure 1. Multi-optical sensing system

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 and therefore the rework required for defect mitigation, the on-line 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.

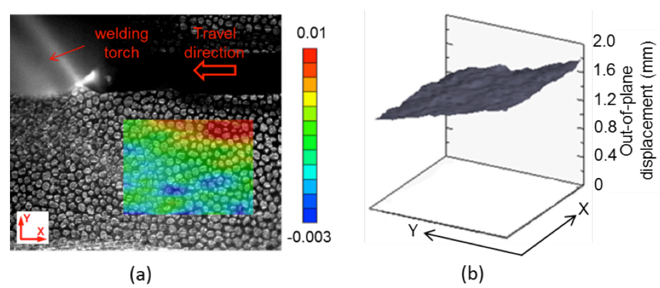

Figure 2. (a) Color map representing strain field (transverse direction) and (b) weld distortion (out-of-plane displacement) within the Region of Interest

Recent Results and Highlights: In the past, the sensing system has been successfully applied to monitor the strain evolution and visualize the weld pool. In the recent year, more efforts have been made to achieve the following major accomplishments: 1) A stereo camera system was integrated to obtain more accurate strain measurement by means of 3D digital image correlation (DIC). Accordingly, a new 3D DIC algorithm and procedure immune to specular reflection of metal surface was developed. It was applied to obtain not only the surface strain evolution, but also the 3D deformation information during welding (Figure 2). 2) A new procedure was developed to determine the stress evolution from the DIC strain measurement in real time. 3) New image processing algorithms were developed to extract the weld pool characteristics and correlate them to certain weld defects such as sidewall lack of fusion (Figure 3).

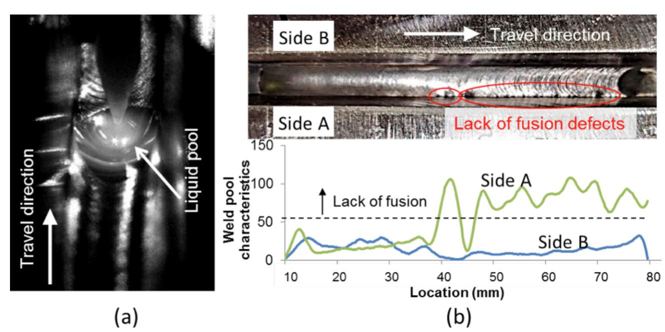

Figure 3. (a) Weld pool visualization and (b) weld pool characteristics and the correlation to lack-of-fusion defects

Additive Manufacturing Awards

Development of Nuclear Quality Components Using Metal Additive Manufacturing

P. Frigola, RadiaBeam Systems, LLC
P. Morton, C. A. Terrazas, A. Hinojos, J. Mireles, L.E. Murr, R.B. Wicker, W.M. Keck Center for 3D Innovation, University of Texas at El Paso
P. Hosemann, A. Reichardt, Department of Nuclear Engineering, University of California at Berkeley
Funding: $999,579 (07/28/2015 to 07/27/2017)

Description of Project: This project aims to optimize and commercialize an electron beam melting (EBM) additive manufacturing (AM) process for joining austenitic steels to nickel-based superalloys, as well as develop the capability (using EBM AM) to efficiently join ferritic to austenitic steels components to overcome a major challenge in the nuclear power industry. The use of EBM AM can help avoid the use of filler materials, provides an evacuated processing environment resulting in limited contamination of oxides and nitrides, and can provide a high quality metallurgical joint while minimizing the thermal damage to surrounding material.

Impact and Value to Nuclear Applications: The successful completion of this project will allow new advancements in directed EBM AM of multi-materials and welding of dissimilar metal alloys. This technology is directly applicable, among others, to the nuclear industry, to fabricate multi-material joints. Figure 1 is an overview of the process to achieve multi-material parts starting from a precursor powder material.

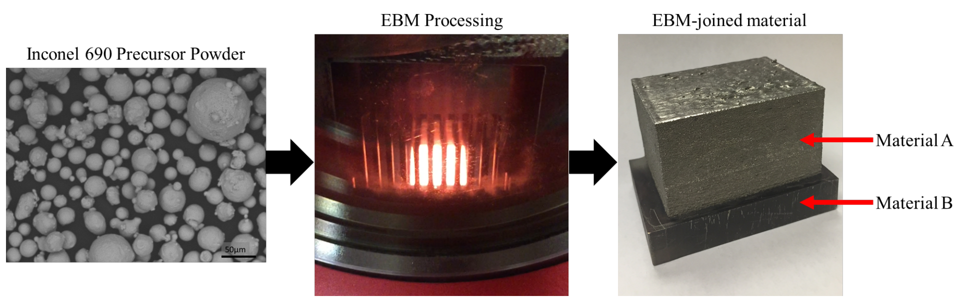

Figure 1. Joining process for non-standard materials

Recent Results and Highlights: Multi-material tensile bars and irradiation targets fabricated using EBM AM at University of Texas at El Paso's (UTEP) Keck Center for 3D Innovation have been recently characterized using mechanical property assessments and microstructural investigations. The focus was on Inconel 718 and 690 joined to 316L Stainless Steel, as well as a comparison with wrought material.

The mechanical testing results show comparable ultimate and yield strengths to wrought alloys. In a similar fashion when welding, strain and elongation are reduced compared to wrought material. Microstructure of failed tensile samples is ongoing to identify the location of failure.

The first nanoindentation data on as-manufactured and ion beam EBM AM multi-materials were collected. Irradiation of the samples was performed at the Los Alamos National Laboratory (LANL) Ion Beam Materials Laboratory (IBML). Nanoindentation testing was carried out by the University of California at Berkeley on ion beam irradiated EBM joints between Inconel and austenitic stainless steel. In summary it is observed that even the small doses of irradiation (~1 dpa) employed in this study result in significant hardening in both wrought and EBM alloys in a similar fashion. However, additional microstructural evaluation is necessary to determine the underlying microstructural changes resulting in the hardening.

Environmental Cracking and Irradiation Resistant Stainless Steel by Additive Manufacturing

Raul B. Rebak, Xiaoyuan Lou, General Electric Global Research
Fred List, Oak Ridge National Lab
Gary Was, University of Michigan
Fran Bolger, Myles Connor, David Webber, GE Hitachi Nuclear Energy
Funding: $678,352 (10/01/2015 – 09/30/2017)

Description of the Project: This project aims to support General Electric's (GE's) goal to evaluate, optimize, and commercialize an additive manufacturing (AM) process to manufacture stainless steel components for reactor internals. The project is to access the nuclear specific properties (e.g., stress corrosion cracking (SCC) and irradiation resistance in high temperature water) of AM stainless steel by laser powder bed fusion (L-PBF). Based on the learning, the project will also optimize and improve these properties. The data generated by this program will contribute to the nuclear specification development for L-PBF process. As a reactor designer and nuclear service provider, General Electric Hitachi Nuclear Energy (GEHN) will facilitate the fabrication and evaluation of a prototype reactor component to demonstrate both schedule and cost savings and lay out business plans for regulatory approval and commercialization.

Impact and Value to Nuclear Applications: L-PBF additive manufacturing has been widely studied in various industries including nuclear. The technology can rapidly fabricate custom designed parts required during plant refueling outages. It can also provide unique capability to generate complex geometries rapidly with improved performance of the components. This project will assist GE to accelerate the development of additive manufacturing technology in its nuclear business. The project will fill the technical gaps and generate valuable SCC and irradiation data of AM stainless steel in nuclear environments. Fundamental understanding of material microstructure and properties can lead to advanced AM stainless steel with improved performance. The current project will make a great impact on commercializing nuclear additive manufacturing, including developing nuclear specifications, supporting regulatory approval, and demonstrating a fuel component with enhanced performance. If all the results are positive, GE will plan to put a prototype product into a commercial power plant.

Recent Results and Highlights: Up to date, the project has made significant progress in multiple areas, including fundamental understanding of SCC and irradiation behaviors of AM stainless steel in simulated nuclear environments, optimizing AM stainless steel (both in chemistry and fabrication process) for nuclear needs, creating new materials with improved nuclear specific properties, and developing fabrication strategies for fuel components. With the optimized laser process and heat treatment, AM stainless steels exhibit low defect density, good mechanical properties and toughness, reasonable corrosion fatigue and SCC crack growth rate (Figure 1), and low irradiation assisted SCC susceptibility. The research has found a strong correlation between process parameters and final material microstructure, which can lead to large vendor-to-vendor variations. Microstructure features such as secondary phase inclusions were found to lead to grain boundary attack in hot water. The powder chemistry was optimized to eliminate precipitates. The team also investigated some innovative concepts to improve SCC and irradiation resistance of AM stainless steel, including higher Ni and Cr content, and nano-oxide dispersion. These alternative alloys have been recently fabricated for testing. Current data suggest AM stainless steel shows promising properties to be used in SCC susceptible and radiation environment. The GE team has successfully developed a fabrication strategy for an advanced debris filter to enhance its performance in service. The team has also completed a roadmap for regulatory approval and has begun drafting the material specification.

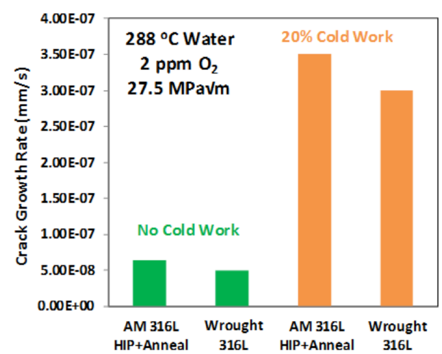

Figure 1. SCC growth rate comparison between AM and wrought (traditional) 316L stainless steel

Advanced Onsite Fabrication of Continuous Large-Scale Structures

Corrie I. Nichol, Idaho National Laboratory

Funding: $799,309 (10/01/15-09/30/18)

Description of Project: Large structures such as pressure vessels and containment structures for gigawatt sized reactors present significant transportation challenges, as do pressure vessels and containment vessels for small modular reactors (SMR). This limits their placement to areas accessible by navigable water ways. This project is conducting initial development work toward a novel method for on-site fabrication of continuous large-scale structures such as pressure or containment vessels.

Impact and Value to Nuclear Applications: This project seeks to leverage the benefits of additive manufacturing in reactor fabrication. Potential benefits include the ability to fabricate vessels from metal matrix composites, or a base material with clad metal structures. This process also enables raw materials to be brought to the construction site in an easily transportable form, where they are melted prior to or during the spraying process. This eliminates the need to weld multiple small sections to form the vessel, eliminating the potential to form undesirable tensile residual stress states at welded interfaces.

Figure 1. Spray deposition process.

Recent Results and Highlights: This project has completed the mid-year milestone of demonstrating and producing sample material. A dual wire arc spray system was selected as a surrogate for spray forming in initial proof of concept testing, and has been used for deposition of material on both ceramic, and metal substrate material. Initial results of the arc spray system are promising.

Deposition of metal on cold ceramic material was shown to result in poor adhesion of deposited material, and was not able to form a cohesive layer. During processing, it was seen that after deposition of an initial layer, the initial layer failed to adhere to the ceramic material sufficiently to be retained on the form during subsequent passes. It was demonstrated that better results could be obtained by spraying material on a heated form to reduce the thermal expansion differential between passes, resulting in better deposition success, and lower residual stresses. This is expected to be an important feature of a spray forming based material deposition system, where thermal management is critical to ensure that subsequent material deposition passes adhere, and material solidifies rapidly upon deposition. Figure 1 shows the deposition process on a ceramic form.

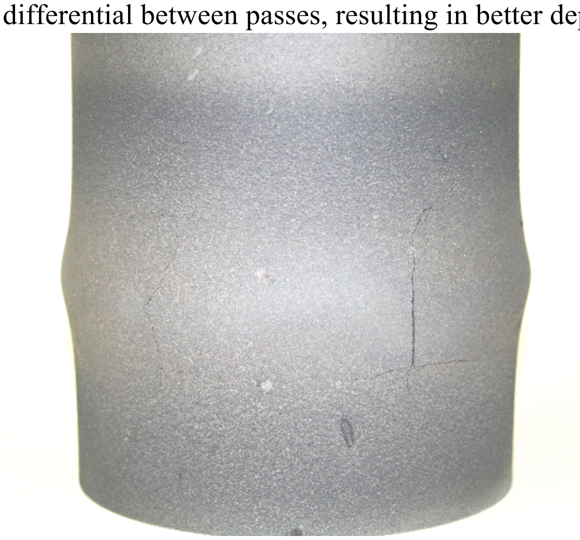

Figure 2. Sample with spray deposited material.

Figure 2 is a material sample consisting of a thick layer of material deposited on a metallic substrate. Development will now continue to determine optimal substrate temperature to obviate cracking in deposition layers, and to develop in-process monitoring and non-destructive examination (NDE) methods that can be used during the deposition of material in a large-scale fabrication process.

Integrated Computational Materials Engineering (ICME) and *In-situ* Process Monitoring for Rapid Qualification of Components Made by Laser-Based Powder Bed Additive Manufacturing (AM) Processes for Nuclear Applications

D. Gandy and C. Stover (Electric Power Research Institute)
R. Dehoff, S. Babu, and F. List III (Oak Ridge National Laboratory-UTK)
D. Poole and T. Hare(Rolls-Royce)
W. Cleary and C. Armstrong (Westinghouse)
Funding: $999,000 (10/01/2016-09/30/19)

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).

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.

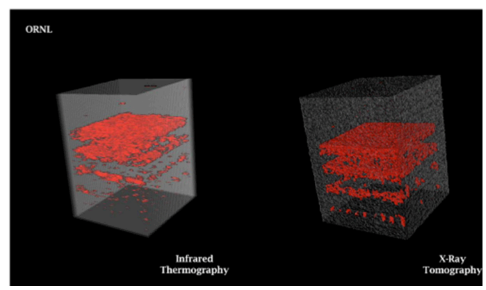

Figure 1. Comparison of infrared thermography vs. X-ray tomography results for a LPB-AM buildup

Recent Results and Highlights: The jointly funded project was initiated in in the third quarter of 2016. To date, much of the effort has been targeted at selecting components to be produced by AM, including a bottom fuel nozzle (Westinghouse), and tee-piece (Rolls Royce). Buildups will be demonstrated using two different alloys: 316L stainless steel and Alloy 718. The SOLIDWORKS model of the tee-piece was completed and models were received for the bottom fuel nozzle. Experimental design of cubes was completed to optimize the process melt parameters. In addition, capabilities for *in-situ* monitoring capabilities were initiated. Finally, infrared imaging was conducted to assess melt conditions, porosity, artifacts, and random defects.

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

Jeffrey C. King, Colorado School of Mines

Funding: $499,928 (10/1/16 - 9/30/21) coupled with Nuclear Science User Facilities access

Description of Project: The project will collect irradiation performance data for stainless steel and Inconel specimens produced using commercially available additive manufacturing (AM) techniques. Tensile bar and thermo-physical property test specimens will be harvested from test articles produced by a representative set of currently available AM techniques. The Colorado School of Mines (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. A subset of the specimens will be irradiated to a range of fast neutron fluences at typical light water reactor temperatures (~600 K) in the Advanced Test Reactor (ATR). Thermo-mechanical testing and micro-structural characterization of the irradiated specimens will be conducted at the Nuclear Science User Facilities (NSUF) post-irradiation examination facilities. The remaining un-irradiated specimens will be thermally aged at Mines and subjected to post-aging thermo-mechanical testing and micro-structural characterization. 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 AM 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 AM parts to meet nuclear quality assurance requirements; and 2) a lack of data related to the irradiation and thermal performance of AM parts, which limits confidence that these parts can survive in the challenging environments needed for nuclear energy applications.

Recent Results and Highlights: Mines is currently developing the test article (Figure 1) to be produced by commercial AM vendors using the four technologies of interest – powder bed electron-beam sintering, powder bed laser sintering, laser powder fabrication, and electron beam free-form fabrication. The test specimens will be machined from the test articles. Engineers from the NSUF are currently designing the test capsule. Insertion of the test items into the ATR is currently scheduled for July 2017.

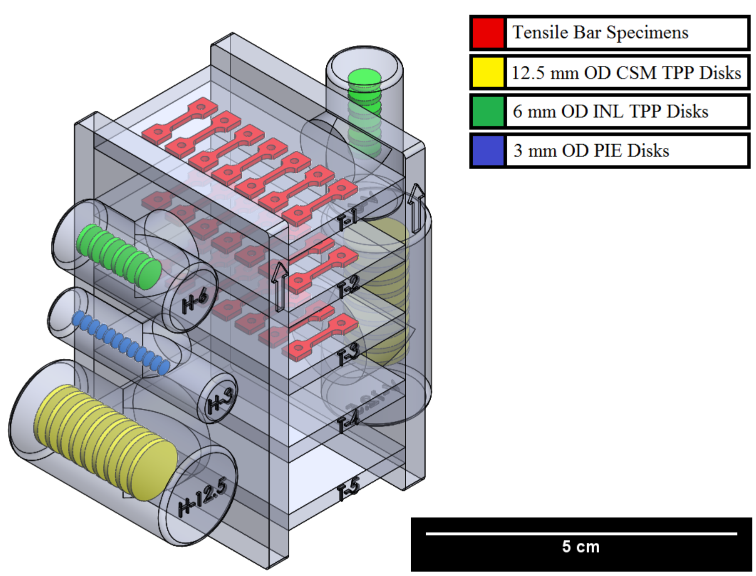

Figure 1. Test article and test specimen sample locations.

Enhancing Irradiation Tolerance of Steels via Nanostructuring by Innovative Manufacturing Techniques

Haiming Wen, Idaho State University
James I. Cole, Yongfeng Zhang, Isabella J. van Rooyen, Idaho National Laboratory
Funding: $500,000 (10/1/2016 – 9/30/2023, coupled with NSUF facility access)

Description of the Project: This project involves neutron irradiation and post-irradiation examination of bulk nanostructured austenitic and ferritic/martensitic (F/M) steels, which are expected 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 objective is 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. It also will assess the potential use 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 holds the potential to improve radiation tolerance at a relatively low cost compared to the development of new alloys.

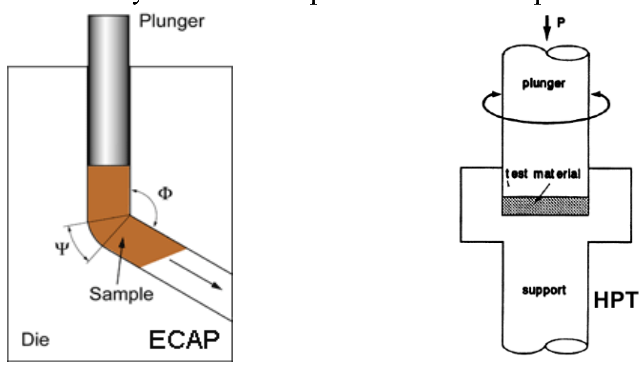

Figure 1. Schematic of equal-channel angular pressing (ECAP) and high-pressure torsion (HPT)

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 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: Preliminary pre-irradiation characterization was performed of bulk nanostructured austenitic steels (304 and 316 steels) manufactured by ECAP and HPT. Microhardness measurements indicated that these steels have significantly higher hardness/strength compared to their conventional coarse-grained counterparts. From transmission electron microscopy studies, the grain size of the ECAP sample is in the UFG range, and that of the HPT sample in the NC regime, verifying that ECAP and HPT can produce UFG or NC structures in these austenitic steels. Second-phase particles (e.g., Ni-rich, Cr-rich and Cu-rich second-phase particles) were found in these UFG or NC austenitic steels, although these steels are nominally single-phase materials. Scanning transmission electron microscopy coupled with energy-dispersive x-ray spectroscopy was used to study the distribution and composition of these second-phase particles. Atom probe tomography was applied to further investigate these second-phase particles and possible grain boundary solute segregation. A preliminary understanding of the microstructure of the UFG or NC austenitic steels has been accomplished. Mechanical testing and microstructural characterization are also being performed on UFG or NC F/M Grade 91 steel. Preliminary neutron irradiation design has been performed. Materials to be neutron irradiated are being machined into specific geometry and dimensions.

Modular Fabrication Awards

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

D. Gandy and C. Stover, Electric Power Research Institute
K. Bridger and S. Lawler, Nuclear-Advanced Manufacturing Research Centre
Funding: $2,500,000 (5/01/2017-4/30/21)

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).

Impact and Value to Nuclear Applications: Through use of technologies including: electron beam welding, 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: The jointly funded project was initiated in the fourth quarter of 2016. To date, much of the effort has been targeted at the creation of multiple SOLIDWORKs drawings for the two-thirds scale components (performed by NuScale Power). Significant planning and scheduling has taken place to allow the manufacture and fabrication of the lower and upper reactor assemblies. A508 powder has been atomized for the production of the lower assembly components. In addition, detailed planning is underway for the manufacture and fabrication of the lower reactor head, the first task in the project. Several early subcontractors have also been selected. Over the next several weeks, the investigators plan to complete the design of the lower reactor head and then begin fabrication of the cans (capsules) to produce halves of the head. The lower reactor head will be produced using PM-HIP, a technology demonstrated in the Department of Energy's Nuclear Energy Enabling Technologies (NEET) program over the past several years.

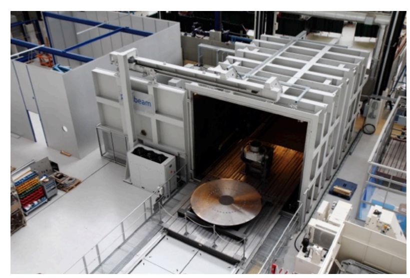

Figure 1. Large electron beam welding chamber at the Nuclear AMRC which will be used to assemble SMR components

Concrete Materials and Rebar Awards

Periodic Material-Based Seismic Base Isolators for Small Modular Reactors

Y. L. Mo, University of Houston
Y. Tang, Argonne National Laboratory
R. Kassawara, Electrical Power Research Institute
K. C. Chang, National Center for Research on Earthquake Engineering, Taipei, Taiwan
Funding: $800,000 (10/01/2014 – 09/30/2017)

Description of Project: The research seeks to develop a periodic foundation for a small modular reactor (SMR) using innovative periodic material. This material is inspired by the concept of a phononic crystal in solid-state physics. This material has a distinct deficiency; it lacks certain frequency bands known as frequency band gaps that let elastic waves pass through if frequencies of waves fall into these gaps. This deficiency, however, is a much needed feature for the seismic base isolation system. With a proper design, the periodic foundation will be able to block incoming seismic waves, preventing them from reaching the superstructure. The focus of this research is placed on the design phase of periodic foundations for the SMR building. The design procedure developed will be validated by shake table tests using real recorded earthquake ground motion.

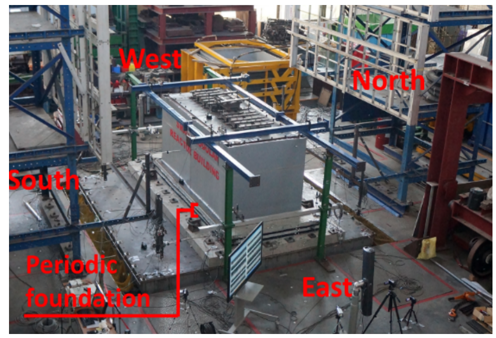

Figure 1. Test setup

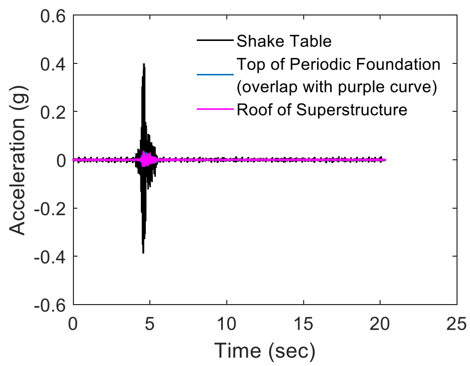

Figure 2. Acceleration responses in time domain

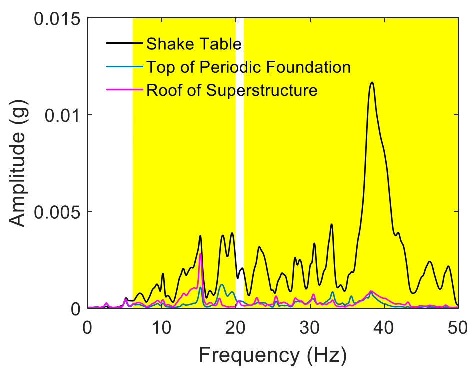

Figure 3. Acceleration responses in frequency domain

Impact and Value to Nuclear Applications: The value of periodic material for SMR foundation applications is twofold. First, it reduces the seismic motion transmitted to the superstructure so that standardization of the nuclear power plant design is feasible. Second, it eliminates the need for a moat surrounding the isolated structure, which is required by the conventional seismic isolation systems such as the rubber bearing and friction pendulum system. This not only reduces construction cost but also avoids hassles related to the design of utility lines crossing the moat.

Recent Results and Highlights: The principle theory of a one dimensional (1D) periodic foundation has been verified through a series of shake table tests. Figure 1 shows the test setup of a four-layer 1D periodic foundation supporting a small modular reactor (SMR) building. The seismic test result (Figure 2) shows a large reduction in the acceleration response at the top of the periodic foundation and at the roof of the superstructure in comparison to the input acceleration or the acceleration recorded at the shake table. The results clearly denote that the periodic foundation altered the seismic wave when it traveled through the periodic foundation. The main frequency content of each acceleration record is shown in Figure 3. It is observed that the periodic foundation filtered the main frequency content of the input acceleration in the frequency range of 3.7 Hz -50 Hz. This frequency range corresponds to the designed frequency band gap, shown by the yellow shaded areas in Figure 3.

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
Funding: $800,000 (10/1/15-9/30/18)

Description of Project: This project aims to reduce the field construction times and fabrication costs of reinforced concrete (RC) nuclear safety-related building 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 of the project is not to develop new innovations on materials, but rather to fill a major knowledge gap on the effectiveness, code conformity, and viability (i.e., practicality, commercial availability) of the application of existing high-strength materials in nuclear structures, especially in stocky shear walls since they are the most common lateral load resisting members in non-containment nuclear structures.

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 costs of material/shipping/fabrication, facilitate concrete placement/consolidation, and also improve construction quality and ease of inspection.

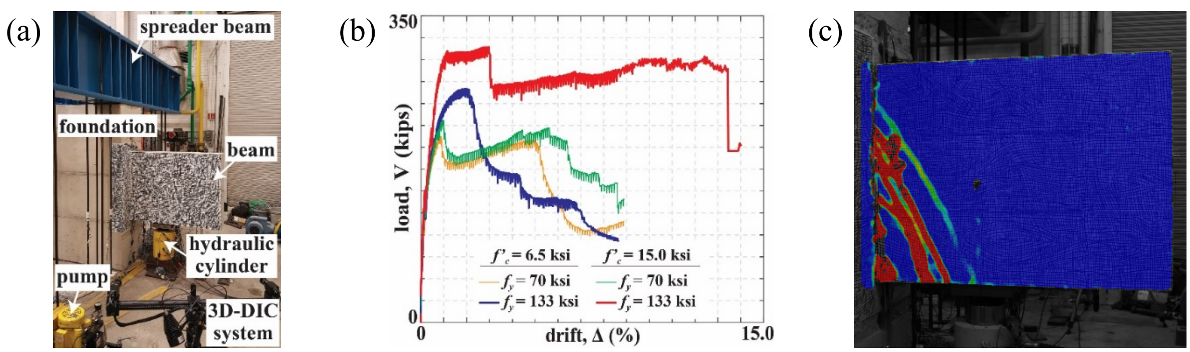

Figure 1. Deep beam testing: (a) setup; (b) applied load versus drift behavior of four specimens with different f_y and f'_c; (c) maximum principal strains at peak lateral strength of specimen with f_y=133 ksi and f'_c=15.0 ksi. (Note: f_y=rebar yield strength, f'_c=unconfined concrete strength)

Recent Results and Highlights: To date, the project tested four deep cantilever beams (representing slices out of the length of a prototype shear wall) under monotonic lateral loading to understand the effects of concrete strength and rebar strength on the lateral load behavior of stocky RC shear walls. Figure 1(a) shows the test setup and Figure 1(b) presents the applied load versus drift behavior for the specimens. The specimen with high-strength steel (f_y=133 ksi) and high-strength concrete (f'_c=15.0 ksi) resulted in the greatest lateral strength and ductility, demonstrating the benefits of combining high-strength steel and concrete. The concrete surface deformations and strains of each specimen were measured using three-dimensional Digital Image Correlation [e.g., Figure 1(c)], resulting in unprecedented information on the governing deformation modes. In addition to the experimental work, the project developed and validated nonlinear numerical models to quantify the construction cost savings (up to 50%, depending on the wall properties) that can be achieved through the use of high-strength materials in nuclear RC shear walls. Comparisons of the measured lateral strengths with code-based predictions demonstrated inadequacies in the current design equations for stocky shear walls, pointing to the need for further research in this area.

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

A. H. Varma, Purdue University

Funding: $800,000 (10/01/2014 – 09/30/2017)

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 steel-concrete (SC) and reinforced concrete (RC) walls subjected to combined accident thermal loading and earthquake shaking, including design basis Safe Shutdown Earthquake (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 American Concrete Institute (ACI) 349 and American Institute of Steel Construction (AISC) N690 (design and detailing) and American society of Civil Engineers (ASCE) Standards 4 and 43 (analysis and design).

Cycle No.	Surface Temperature	Heating Duration	Target Force/Disp. Level
1	Ambient	-	$0.25P_y$
2	Ambient	-	$0.50P_y$
3	Ambient	-	$0.75P_y$
4	300°F	1 hr	$0.75P_y$
5	300°F	3 hr	$0.75P_y$
6	450°F	1 hr	$0.75 P_y$
7	450°F	3 hr	$0.75 P_y$
8	450°F	1 hr	$1.0 \Delta_y$
9	450°F	3 hr	$1.0 \Delta_y$
10	450°F	1 hr	$1.5 \Delta_y$
11	450°F	3 hr	$1.5 \Delta_y$
12	450°F	4 hr	$2.0 \Delta_y$

Figure 1. Loading cycles for SC wall pier specimen: Specimen subjected to different intensities and durations of heating

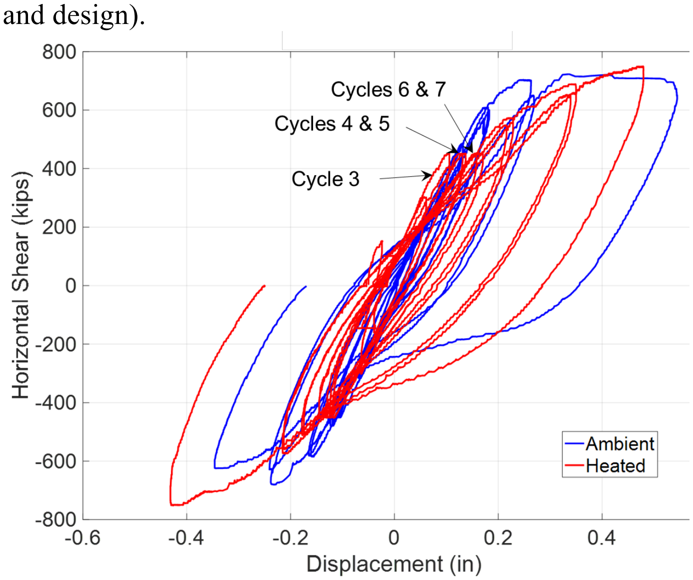

Figure 2. Effect of thermal loading on stiffness and strength: Comparison of heated specimen with control specimen

Recent Results and Highlights: Experimental studies were conducted on SC wall pier specimen. The specimen was subjected to the loading cycles presented in Figure 1. The experimental results indicate that thermal loading significantly reduces the lateral stiffness of the specimens (as seen for cycles 3 to 7, and comparison of post yield cycles for ambient and heated specimens, in Figure 2). The maximum surface temperature (300 → 450ºF) has reasonable influence, and the heating duration (1 hour versus 3 hours) has marginal influence on the wall lateral load response. Additionally, the lateral load capacity of the heated specimen was similar to the ambient specimen (Figure 2), since the failure mode was governed by in-plane flexural yielding.

Surface Modification and Cladding Awards

Advanced Surface Plasma Nitriding for Development of Corrosion Resistant and Accident Tolerant Fuel Cladding

Robert Balerio[1], Hyosim Kim[1], Lin Shao[1], Don Lucca[2]
[1]Texas A&M University [2]Oklahoma State University
Funding: $800,000 (10/01/2015-09/30/2018)

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 DOE interest, the team will apply 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. Development of advanced fuel cladding materials is critical for both present designs with extended lifetimes and advanced designs with even harsher operation conditions. Although numerous studies have shown that a surface nitride layer can be used to 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 a hollow tube.

Recent Results and Highlights: The team has demonstrated the feasibility of the technique to nitride Fe, 316L, HT-9, T91, Zr, and Zircaloy. A Cathodic Cage Plasma Nitriding (CCPN) device was built and optimized for the best performance. Systematic nitridation experiments were performed under various pressure, temperature and nitridation time. Growth kinetics were extracted for each material to obtain empirical formulas to predict nitride layer thickness under arbitrary nitridation conditions. Nitride phases were characterized by combining a focused-ion-beam technique and transmission electron microscopy (TEM), and compared with phase diagrams to determine the formed phases. Cross-sectional nanoindentation as a function of distance away from the nitride surface shows significantly enhanced hardness within nitride layers. Surface scratching tests show excellent bonding between nitride layers and substrates. For the next steps, nitrided samples will be tested in BWR and PWR-like coolants in both normal and off normal conditions to evaluate the efficiency of nitride layers in reducing oxidation. Furthermore, the project will extend the nitridation experiments to reactor spacer grids of complex geometry to evaluate the extended applications to other in-core components aimed for enhanced accident tolerance.

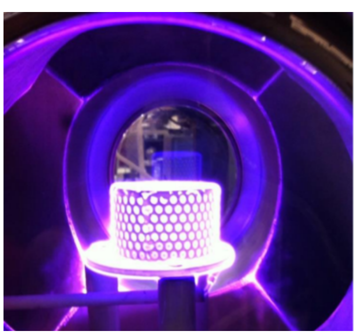

Figure 1. Image of nitridation device under operation.

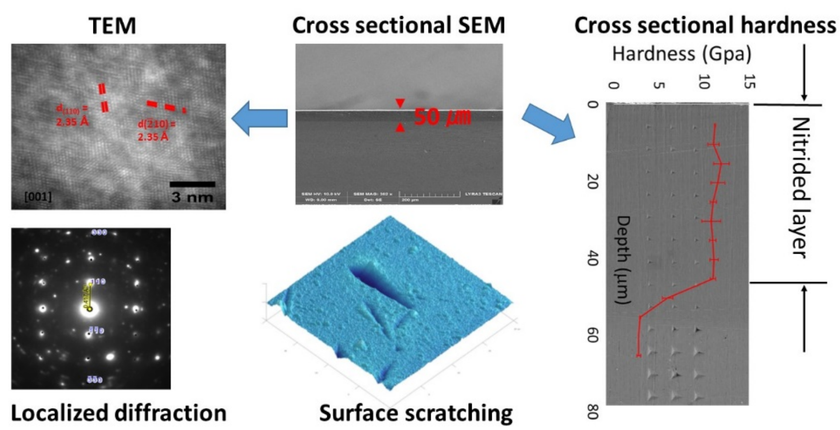

Figure 2. Cross-sectional scanning electron microscopy (SEM) image of the nitride layer and indented region, high resolution TEM and diffraction patterns of 316L after nitridation. Atomic force microscope image of a scratch test on the nitride layer is also shown.

All-Position Surface Cladding and Modification by FSAM

Zhili Feng and Wei Tang, Oak Ridge National Laboratory
Greg Frederick and David Gandy, Electric Power Research Institute
Funding: $800,000 (10/1/2016-9/30/2019)

Description of Project: This research aims at developing a novel solid-state friction stir additive manufacturing (FSAM) process, to clad nuclear internals and components to improve erosion, corrosion and wear resistance, with considerable reduction in cost and improvement in productivity and quality. The research will focus on three major activities: (1) to demonstrate 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) to develop the fundamental understanding and the technical basis to substantiate that FSAM would prevent defects caused by current fusion cladding technologies, such as solidification cracks and ductility–dip cracks (DDC), minimize service degradations, as well as reduce surface residual stresses for several targeted classes of advanced nuclear structural materials, including structural steels, nickel based (high Cr alloys) (Alloy 82 and 52), and austenitic stainless steels (308 and 309L), and (3) to produce 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. Today, fusion welding based processes, i.e. various arc welding processes, are typically used for cladding. 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 and/or other properties are difficult for fusion based cladding due to solidification cracking and DDC that are related with the non-equilibrium melting and solidification processes in fusion cladding technologies and cost industries millions of dollars each year in repair or replacement. 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, (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 improved cladding productivity with high quality and reduced manufacturing cost in nuclear reactor component production and beyond.

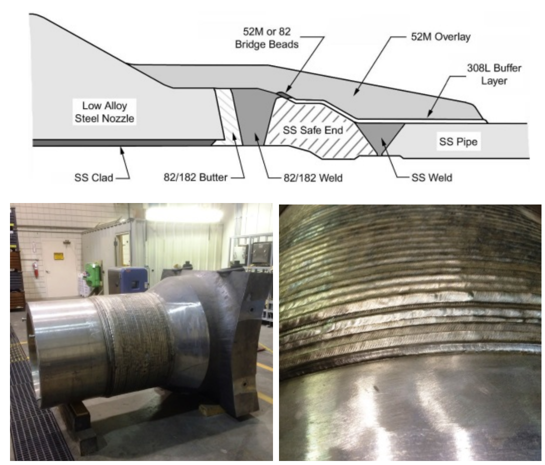

Figure 1. Cladding as butter layer and overlay in DM weld of cold leg to RPV nozzle

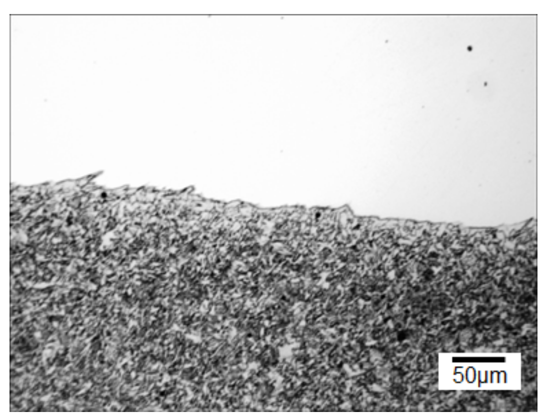

Figure 2. Bonding interface between SS304 (top) and A516 steel (bottom) produced by FSAM

Recent Results and Highlights: In the first 6 months of the project, the research focused on FSAM process optimization to develop the process window for defect-free solid-state bonding. The process innovation also considered the tool wear issue that must be addressed on FSAM. Stainless steel 304 was cladded onto A516 pressure vessel steels in the experiment. High quality, solid-state bonding has been achieved so far, as shown in Figure 2.

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)

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 (7/28/14 – 7/28/16)

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