AMM Newsletter

Advanced Methods for Manufacturing

Issue 9 • March 2019

Advanced Methods for Manufacturing Program Update

The Department of Energy's Office of Nuclear Energy (DOE-NE) Advanced Methods for Manufacturing (AMM) program's primary objectives are to identify and pursue research that can reduce the construction time of new nuclear plants by six months or more, or reduce the cost of components for nuclear power plants by at least 20 percent. The AMM program has supported more than 25 projects since its inception in 2012, and continues to make progress toward these goals.

Currently, AMM projects are funded through the Consolidated Innovative Nuclear Research (CINR) / Nuclear Energy Enabling Technologies (NEET), the Industry Funding Opportunity Announcement (IFOA), and the Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR) programs.

In Fiscal Year (FY) 2018, two projects were added to the AMM program through the CINR awards. The Massachusetts Institute of Technology is exploring nano-dispersion strengthened metallic composites with enhanced neutron irradiation tolerance. The University of Pittsburgh is using a dissolvable support technology to effectively remove both the internal and external support structures of additive manufacturing builds with the goal of achieving a drastic reduction in the cost of complex nuclear components.

The AMM program also awarded a new two-year project to the Electric Power Research Institute to establish modular in-chamber electron beam welding that will dramatically cut the time to join large, thick section components.

Four SBIR Phase 1 projects were also added to the AMM program. Polar Onyx plans to integrate additive manufacturing (AM) and subtractive manufacturing into an intelligent system for controllable manufacturing.

LER Technologies is developing a real time non-destructive evaluation system with optical sensors for 3D manufacturing of metal parts. Brimrose Technologies will prototype a system for inspecting components using an UltraSonic Scattering Technique. In addition, NovaTech is using the unique capabilities offered by AM to design a lower tie plate for a boiling water reactor fuel assembly that can be used in a lead test assembly.

Ensuring that the U.S. has the capability to support the manufacturing requirements of the various domestic advanced nuclear reactor designs, including small modular reactors, is critical to their commercial

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For more program information, including recent publications, please visit www.energy.gov/ne

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deployment. MPR Associates conducted an assessment and provided a report which is summarized on page 3 of this newsletter. The full report is available at https://www.osti.gov/biblio/1494317-united-states-nuclear-manufacturing-infrastructure-assessment.

Finding pathways for the qualification and regulatory acceptance of AMM-related technologies is receiving increasing attention from DOE-NE, the Nuclear Regulatory Commission (NRC), and nuclear industry trade associations. The NRC released its Advanced Manufacturing Technologies (AMT) Draft Action Plan in February 2019, which can be found at https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML19031C843 and at https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML19029B355

The AMM program held its annual program review meeting December 4-6, 2018, at the Manufacturing Demonstration Facility (MDF) in Knoxville, TN. The purpose of this meeting was to review the currently funded projects encompassing additive manufacturing, welding and joining technologies, concrete materials and rebar innovations, and surface modification and cladding processes. The presentations are available at https://www.energy.gov/ne/downloads/fy-2018-advanced-methods-manufacturing-program-review-meeting

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United States Nuclear Manufacturing Infrastructure Assessment

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The existing U.S. manufacturing infrastructure was evaluated to ascertain gaps that could inhibit U.S. industrial support for deployment of small modular reactors (SMRs) or advanced reactors. This project compared the needs of SMRs and advanced reactors against the capability of U.S. manufacturers to manufacture, on a commercial scale, the major components and unique materials required by various U.S. designs for SMRs and advanced reactors. This project was completed in December 2018.

Reactor-plant designs being developed by NuScale Power (the NuScale Power Module), TerraPower (both the Traveling Wave Reactor and the Molten Chloride Fast Reactor, to a limited extent), and X-energy (the Xe-100) were considered in the evaluation. MPR visited each of these companies and selected candidate suppliers to tour their facilities and conduct in-person interviews. Information was also obtained by telephone interviews, internet research, and review of technical reports. The key conclusions and recommendations from this effort are outlined below.

Conclusions

Manufacturing Needs for SMRs and Advanced Reactors

Most of the components needed for the designs considered in this study are within the capability of the U.S. manufacturing infrastructure. The principal capability gaps are associated with reactor pressure vessels, steam generators (SGs), and fuel fabrication.

Many components for SMRs and advanced reactor designs will be first-of-a-kind (FOAK), first-in-a-while (FIAW), or customized for the parameters of a particular design. While such components are subject to the typical challenges for manufacturing unique items, they are generally expected to be within the capability of the U.S. infrastructure.

For a high construction rate of SMRs and advanced reactors, the capacity of the existing U.S. manufacturing infrastructure may be insufficient. However, all manufacturers indicated a willingness to expand capacity when there are sufficient orders to justify investment.

The lack of new nuclear construction projects in the U.S. in the immediate term will continue to erode U.S. capabilities and capacities for supporting new plants. By the time SMRs and advanced reactors are ready to be widely deployed, the capability and capacity of the U.S. manufacturing infrastructure to support new plants may be less than at the time of this study.

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Review of Manufacturing Methods

MPR reviewed a range of manufacturing methods including forging, tube drawing, machining, fabrication, powder-metallurgy hot-isostatic pressing (PM-HIP), and additive manufacturing (AM). Key conclusions from this review included the following:

- While the forgings planned for SMRs and advanced reactors may be smaller than for Generation III+ plants, there are still some forgings that exceed the capability of U.S. forges.
- All three designs in this study use helical coil steam generators (HCSGs), which differ from existing commercial designs. HCSGs require longer SG tubes, and no domestic supplier possesses sufficient capabilities to meet all of the specifications.
- The advanced reactors from this study have novel fuel designs requiring new manufacturing processes to produce high quality fuel assemblies at a high yield. The fuels use high-assay low-enriched uranium (HALEU), for which there is no existing commercial domestic facility for providing enrichment.
- With a few exceptions, the capabilities currently exist to machine and fabricate components of the size required for SMR or advanced-reactor components.
- Plant designers and component suppliers acknowledged the potential benefits of PM-HIP and AM, but considered that these methods were too far from commercial deployment to affect current supply chain plans.

Recommendations

Based on the results of this study, MPR developed recommendations to address gaps in the U.S. manufacturing infrastructure and other issues related to deployment of SMRs and advanced reactors, including the following:

- Support selection of U.S. suppliers for FOAK or FIAW components by investing in existing U.S. facilities that use conventional manufacturing processes (e.g., manufacturing demonstrations). Mechanisms for supporting such efforts already exist, but appear to be targeted more for longer-term research. Funding for nearer-term applications would benefit the existing manufacturing infrastructure.
- Support commercial uranium enrichment and development of shipping containers for advanced reactor fuel. U.S. competitiveness would be enhanced by avoiding the need for each reactor vendor to independently develop fuel fabrication and shipping capabilities.
- Investigate and promote avenues to mitigate the risks for U.S. manufacturers supporting nuclear projects. Manufacturers are leery of making investments for the nuclear industry without orders being placed and reasonable assurance that those orders will be carried through to completion.
- Continue to invest in advanced manufacturing methods. U.S. manufacturers and plant designers noted there is little incentive for them to achieve technological breakthroughs at this time. DOE support will be necessary to move these technologies forward.

Incentivize construction of multiple plants by commercial entities and seek opportunities for SMRs or advanced reactors among U.S. government assets. DOE support may be necessary to offset the high cost for initial builds and allow the designs an opportunity to demonstrate their potential for cost effectiveness over multiple projects.

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

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Additive-manufacturing (AM) technologies have the potential to significantly impact many industrial sectors, including the nuclear energy industry. These technologies manufacture parts through a variety of techniques that add material to a developing part in a controlled and reproducible fashion. Parts produced using additive techniques can be produced in nearly any shape or configuration, including many that cannot be produced using conventional manufacturing techniques. In particular, while cost typically scales with complexity in traditionally manufactured parts, there is often little to no penalty for complexity in additively manufactured parts. AM can thus be used to produce unique heat-exchanger geometries or difficult-to-assemble piping unions. AM also offers the potential for quickly and affordably producing one-of-a-kind replacement parts, which can be extremely important in maintaining nuclear power facilities that are more than 40 years old.

Despite these 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 AM techniques, which limits the ability of additively manufactured parts to meet nuclear quality-assurance requirements, and 2) a lack of data related to the irradiation and thermal performance of AM parts, which limits confidence that these parts can survive in the challenging environments needed for nuclear energy applications.

This project will collect irradiation-performance data for stainless steel and Inconel specimens produced using a range of commercially available AM techniques (laser powder bed, laser free form, and electron-beam wire feed). A comparison of the physical properties and microstructure of irradiated specimens to those of 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.

Current Status

Tensile bar and thermo-physical property test specimens have been harvested from material billets produced by a representative range of currently available AM techniques (Figure 1). The Colorado School of Mines (Mines) is conducting pre-irradiation thermo-mechanical testing (tensile strength, yield strength, elastic modulus, ductility, thermal conductivity, and thermal diffusivity) and microstructural

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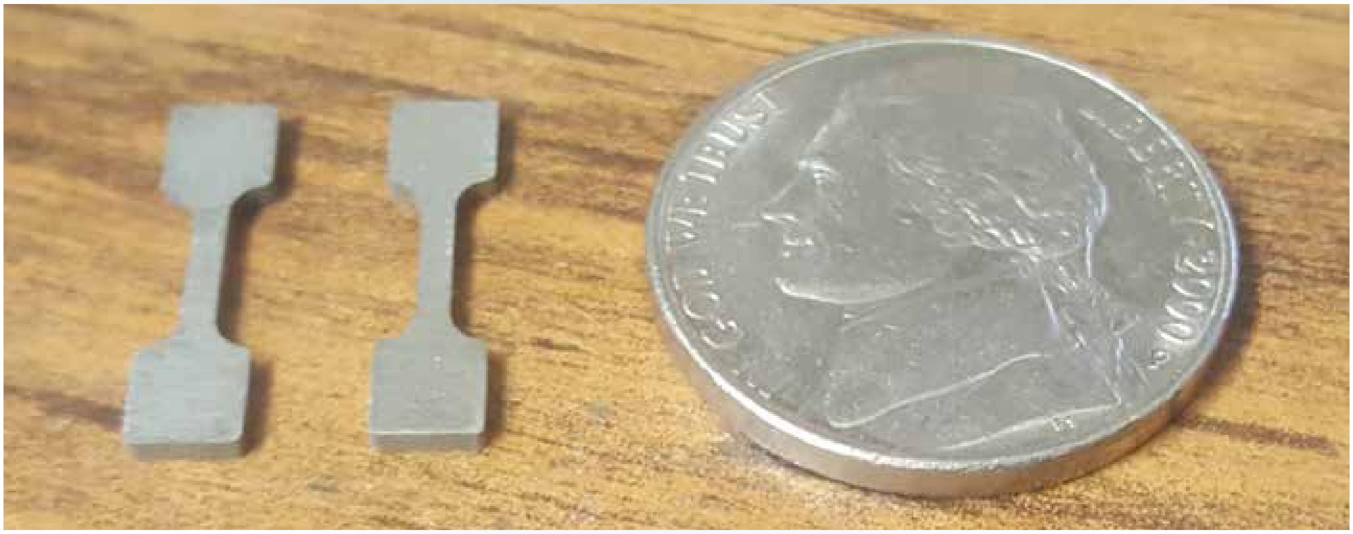

Figure 1. Subminiature tensile bars.

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characterization of the specimens. A subset of specimens has been irradiated to a range of fast-neutron fluences at typical light-water reactor temperatures (~600 K) in the Advanced Test Reactor (ATR, see Figure 2) and are awaiting capsule disassembly and shipping. Thermomechanical testing and microstructural characterization of the irradiated specimens will be conducted at the Low Activation Materials Design and Analysis (LAMDA) facility at Oak Ridge National Laboratory and at the Nuclear Science User Facilities (NSUF) at Idaho National Laboratory.

Recent publications on the properties of AM specimens produced by laser-sintering processes indicate that these materials can exceed the strength/ductility tradeoff shown by conventionally manufactured materials. That is, AM materials can show high strength with greater ductility than conventionally produced materials as a result of the unique microstructures produced by the AM process (Figure 3). Mines is currently developing computational models to predict the stability of these microstructures under irradiation (Figure 4), with the intent of validating these models using results from the characterization of the irradiated specimens.

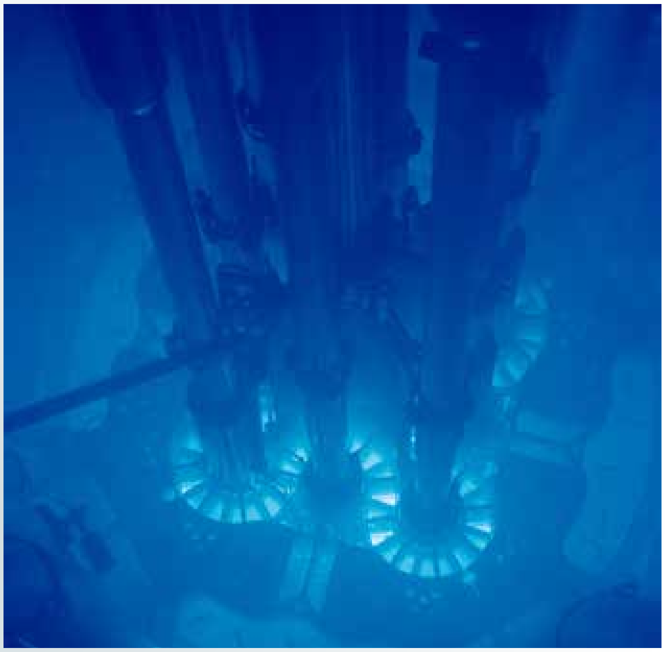

Figure 2. Advanced Test Reactor at the Idaho National Laboratory.

Conclusion

This project will provide high-value data on performance. These data will provide direction for future technology development and testing to meet the quality-assurance and performance needs of the nuclear energy industry and will provide input and benchmark data for future computational modeling efforts related to AM components. Successful completion of the project will provide data for the qualification of AM parts for nuclear applications and may enable the development of tailored microstructures that provide enhanced resistance to radiation damage.

The NSUF continues to provide funding and facility support for this project.

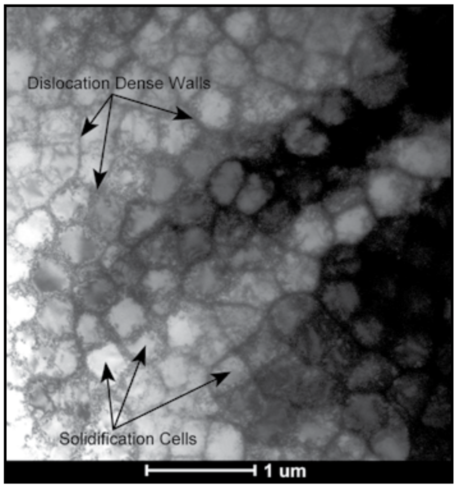

Figure 3. Transmission electron microscopy image of additively manufactured 316L stainless steel.

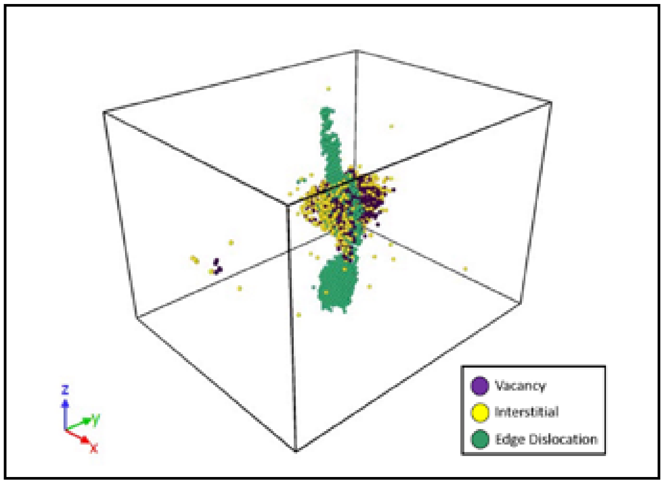

Figure 4. Molecular dynamics simulation of a radiation-damage cascade resulting from a 10 keV primary knock-on atom interacting with an edge dislocation in iron.

All-Position Surface Cladding and Modification by Friction Stir Additive Manufacturing

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Surface cladding and modification are extensively used in the fabrication of nuclear reactor systems, often for improving the resistance to corrosion, erosion, and wear of component surfaces. Various arc welding processes have been widely used for surface cladding. However, considerable challenges exist to apply a number of advanced alloys with superior corrosion resistance and/or other properties by fusion based welding processes such as arc welding cladding, due to solidification related metallurgical incompatibility issues.

Zhili Feng
Oak Ridge National Laboratory

Friction stir additive manufacturing (FSAM) is a novel extension of the solid-state friction stir welding technology. FSAM builds a structure pass-by-pass and layer-by-layer, all in solid-state without melting. Due to its solid phase nature, FSAM has the potential to overcome some major shortcomings of conventional cladding, namely easing the metallurgical incompatibility constraints in the use of new cladding materials, minimizing the microstructure and performance degradations of the high performance structural materials, near zero dilution to reduce the number of cladding layers for material/cost reduction, and an increase in productivity.

The objectives of this research are: (1) to develop and demonstrate the technical viability and economic advantages of FSAM on material combinations that are difficult or impossible with today's fusion-based cladding technologies, (2) to gain fundamental understanding and the technical basis to substantiate that FSAM is capable of eliminating defects such as solidification cracks and ductility dip cracking (DDC), and improving the surface corrosion, erosion, and wear properties, for several targeted classes of structural materials, and (3) to produce prototypical surface cladded components for testing and evaluation to gain acceptance by the appropriate regulatory or standard-setting bodies and licensing for commercial nuclear plant deployment.

Current Status

The project team has successfully demonstrated the viability of cladding multi-material combinations by the FSAM process. An example of multi-layer multi-material cladding is shown in Figure 1. The substrate material

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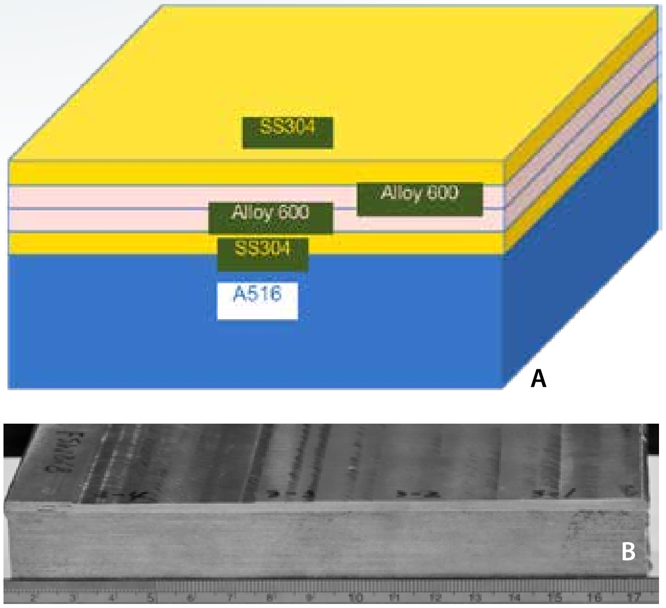

Figure 1. Multi-layer Multi-material FSAM Development. (a) schematics of layout of the cladding materials (b) cross-section of the cladding layer on steel substrates.

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was ASTM A516 Gr70, a structural steel commonly used in pressure vessel construction. Two types of cladding materials, stainless steel 304 and Alloy 600, were selected in the process development. The arrangement of the cladding material stacking is given in Figure 1(a), so chosen that cladding on same materials (such as Alloy 600 to Alloy 600) would be developed, as well as for dissimilar material combinations. Figure 1(b) shows the cladded part. A total of 3.4 mm thick of clad with different material combinations was successfully produced via the FSAM process.

C-scan ultrasonic non-destructive evaluation (NDE) was used effectively to evaluate the bonding quality of large area cladding to assist the FSAM process development. The applicability of C-scan NDE technique was first determined with destructive evaluation techniques such as cross-sectioning of clad to reveal the lack of bonding conditions, as well as guided side bend test. It was found out that the C-scan NDE technique was able to provide macroscopic level determination of the lack of bonding in the 1-mm range. C-scan NDE provided an effective way to assist the FSAM process development and optimization.

Figure 2 shows an example of the C-scan ultrasonic NDE results of the multi-layer clad in Figure 1. The two lack of bonding locations, pointed out by the arrows in the C-scan image and marked in the actual clad, were identified and subsequently repaired by FSAM, by reprocessing the unbonded regions.

The project team also developed a robust FSAM process model to correlate the interface temperature for bonding to the process conditions. Figure 3 shows the predicted temperature distribution during FSAM, and comparisons with experimentally measured peak temperature distribution. This process development modeling tool, while relatively simple, was very fast to allow the project team to quickly evaluate various combinations of process conditions in a matter of few minutes, to assist the optimization and refinement of FSAM process for cladding. One application of the process model was to scale up the tool size to increase the cladded area in one pass to improve cladding productivity. The cladding results by a 1-inch tool are shown in Figure 4. The process condition

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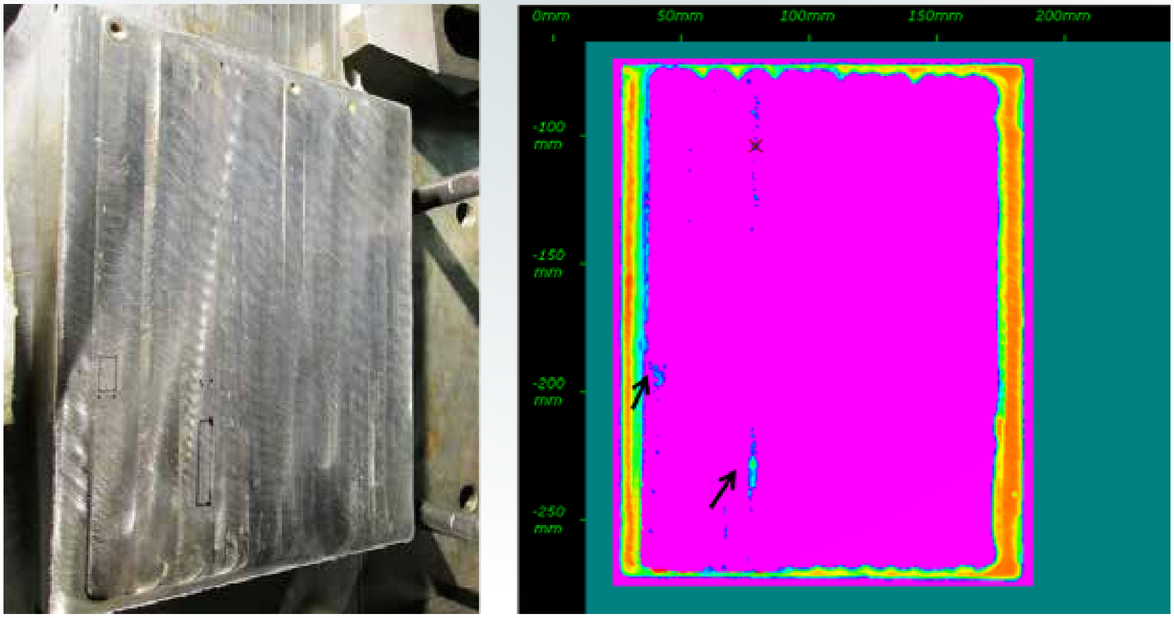

Figure 2. C-scan NDE of multi-layer clad.

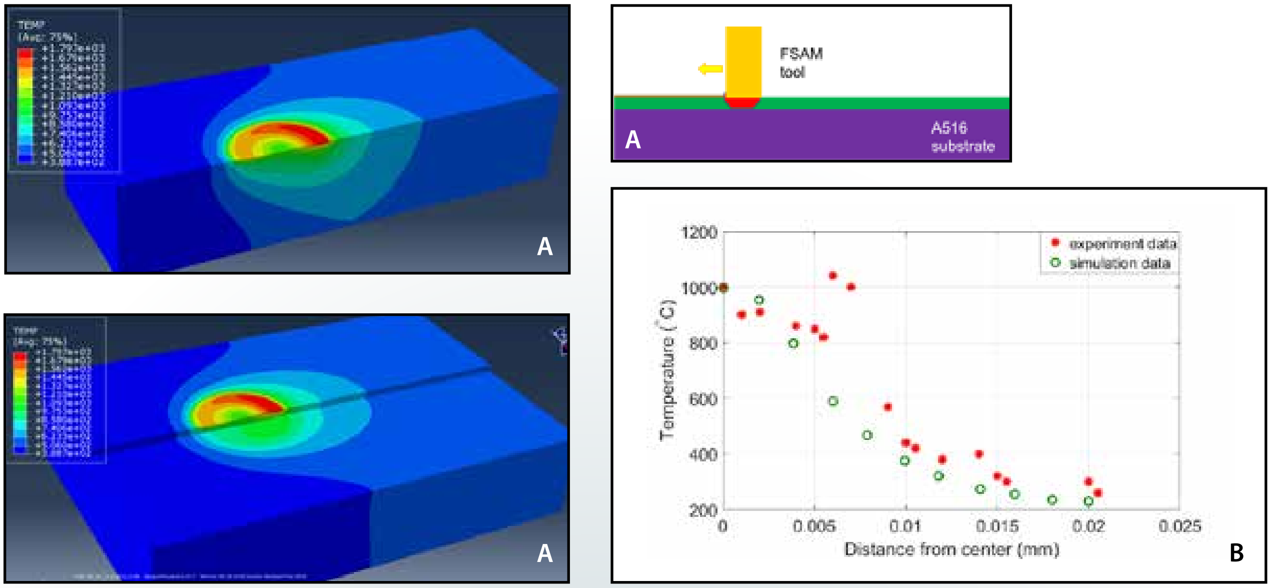

Figure 3. FSAM process model developed to assist the process refinement and optimization. (a) Basics of the model and predicted temperature distribution during cladding, (b) comparison of peak temperature distribution confirming the adequacy of the process model for interface temperature prediction based on process conditions.

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with the 1-inch tool was obtained with the assistance of a process modeling tool developed in the project. The goal is to increase the tool size to 2-inch diameter, to meet that target of a 20 percent overall increase in productivity, compared to typical arc welding based cladding process.

Our research has resulted in potential applications in supporting the life extension of nuclear power plants. A particular potential application is the development of an advanced welding technology to repair highly-irradiated nuclear reactor internals, to overcome the helium induced cracking problem associated with arc welding repair.

Conclusion

This project has made considerable progress. The feasibility of multi-layer, multi-material cladding onto pressure vessel structural steel has been demonstrated. Process scale up to increase the cladding productivity is possible with the aid of a robust FSAM computational modeling tool. Near-term potential application of FSAM for repair of highly-irradiated nuclear reactor internals is identified and will be pursued in coordination with the DOE Light Water Reactor Sustainability program.

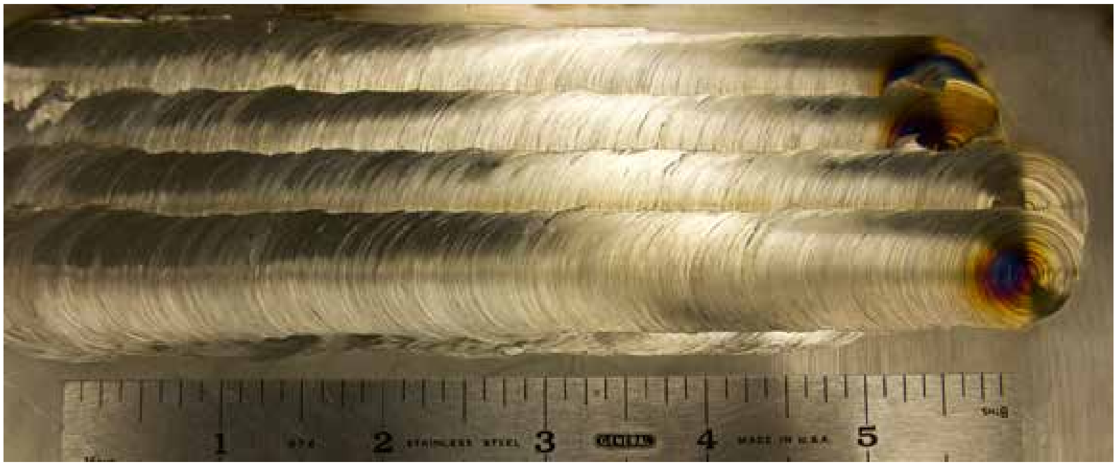

Figure 4. Process scaling up. Successful FSAM cladding with 1” diameter tool.

Development of an Innovative Manufacturing Approach for Oxide Dispersion Strengthened (ODS) Steel Cladding Tubes using a Low Temperature Spray Process





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Progress in advanced-reactor designs requires the development of superior structural materials and cost-effective manufacturing processes. Oxide-dispersion-strengthened (ODS) steels are being widely considered as one of the leading candidate structural material for advanced-reactors concepts such as sodium- and lead-cooled fast reactors (SFRs and LFRs, respectively). Ferritic ODS steels confer good swelling resistance under radiation, and the oxide nanoparticles uniformly distributed in the ferritic matrix impart good high-temperature strength due to their pinning effect on dislocation motion. The interfaces between the nanoparticles and the matrix act as sinks for radiation-induced defects, which further enhances ODS steels' radiation-damage tolerance.

Currently, an arduous process involving powder consolidation followed by multiple extrusion and annealing steps is involved in the manufacturing of ODS steel fuel-cladding tubes. This project investigates a simpler and, possibly, more cost-effective approach involving the use of a cold powder-spray technology for the manufacture of ODS fuel-cladding tubes as an alternative to conventional methods. Another phase of this project involves the development of the cold-spray process as a coating method to mitigate corrosion and wear in nuclear-reactor materials and components. In the cold-spray process, a pressurized, pre-heated gas is used to propel powder particles through a de Laval nozzle onto a substrate at supersonic velocities to form a coating on the substrate, as schematically shown in Figure 1. The interparticle bonding and bonding between the particles and the substrate occur by severe plastic deformation and an associated adiabatic-shear mechanism. The process is performed at ambient temperature and pressure and has the potential for very high deposition rates. Deposition occurs in the solid state, making it especially suitable for ODS steels, as any melting will lead to stratification of the oxide nanoparticles.

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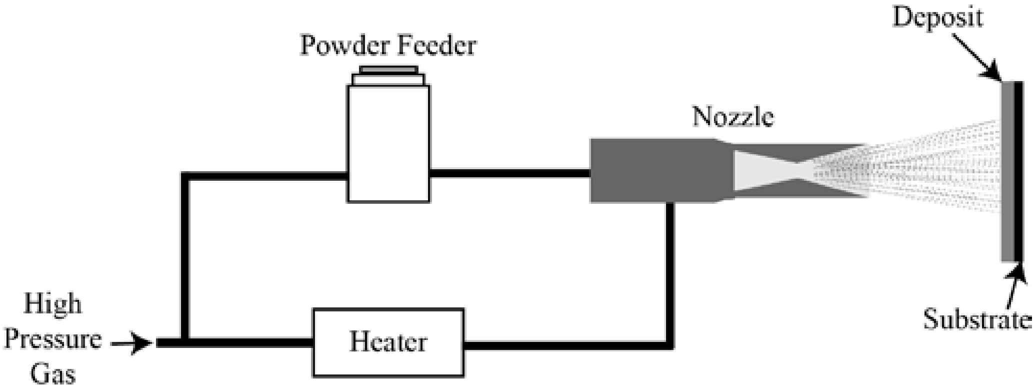

Figure 1. Schematic illustration of the cold spray materials deposition process.

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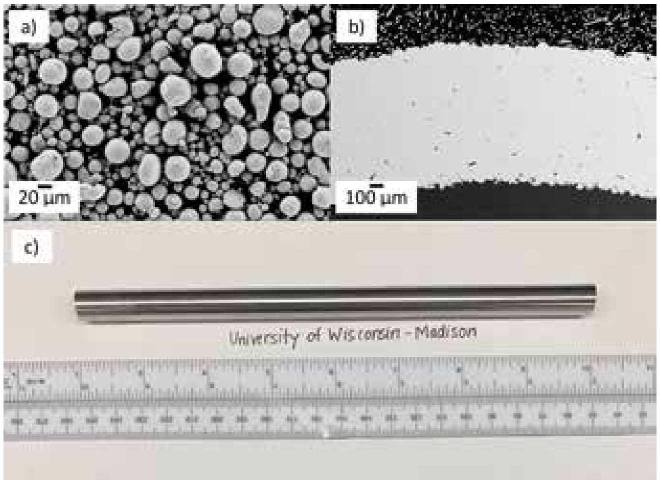

Figure 2. SEM images of (a) 14YWT ODS-steel powder and (b) cross-section of ODS steel deposit produced by the cold-spray process; (c) subsequent surface polishing of the deposit and dissolution of the aluminum-alloy mandrel leaves behind a free-standing ODS steel cladding tube.

The project has successfully manufactured ODS-steel cladding tubes using the cold-spray process using 14YWT steel gas-atomized feedstock powder provided by Oak Ridge National Laboratory (ORNL). The powder had a spherical morphology typical of gas-atomized powders, as shown in Figure 2a with oxide nanoparticles present in the steel matrix. The powders were sprayed onto a rotating aluminum-alloy mandrel with the cold-spray nozzle traversing in the axial direction. Multiple parametric investigations of carrier-gas composition, powder-size distribution, and substrate type were performed to attain high-quality ODS-steel deposits. The cross-sectional scanning-electron-microscopy (SEM) image shown in Figure 2b indicates that a dense and thick deposit (1 mm wall thickness) was achieved. The outer side of the tube was then polished with silicon-carbide abrasive papers to produce a metallic surface finish and the inner aluminum-alloy mandrel was subsequently dissolved in a 20% NaOH solution to leave the freestanding 8-in. (203 mm) ODS-steel tube shown in Figure 2c.

Microstructural characterization of the deposit was performed using both SEM and scanning transmission electron microscopy (STEM). STEM examination of the deposit indicated a dense forest of dislocation and disappearance of the oxide nanoparticles due to their dissolution during the high velocity impact of the particles with the substrate. SEM imaging of the tubes after heat treatment in the temperature range of 800–1100°C showed recrystallization and grain growth. Annealing the tube served a dual purpose: it enhanced cladding ductility and also resulted in the re-precipitation of the oxide nanoclusters inherent to ODS steels. An example of this annealing effect is illustrated in Figure 3a for samples annealed at 1000°C, showing that the dislocations were annealed out while the nanoparticles re-precipitated in the ferritic matrix. Current work is focused on further process optimization by using a powder with increased yttrium and oxygen content to create a greater volume fraction of oxide nanoparticles that can more effectively pin down grain boundaries after recrystallization. Mechanical testing will also be performed to benchmark the cold-spray-produced ODS-steel cladding tubes to the ODS-steel cladding tubes manufactured by the conventional route.

A parallel effort using cold-spray process to deposit coatings for enhanced corrosion resistance is also underway. An example of this effort is shown in Figure 3b, in which an ODS steel tube (also produced by the cold spray process, as outlined earlier) was coated with highly oxidation-resistant FeCrAl (Fe-20Cr-5Al) alloy by the cold spray process. Oxidation experiments with these multilayered deposits, as well as other multilayer coatings, will be performed and developed in the coming quarters.

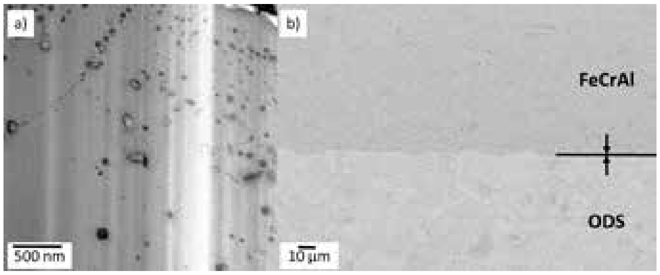

Figure 3. STEM bright-field image of (a) 1000°C annealed ODS steel tube showing re-precipitation of oxide nanoparticles and (b) SEM image of multilayer coating of FeCrAl sprayed on ODS with arrows indicating FeCrAl/ODS interface.

To submit information or suggestions, contact
Tansel Selekler at **Tansel.Selekler@nuclear.energy.gov**.