AMM Newsletter

Advanced Methods for Manufacturing

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Program Update

The Advanced Methods for Manufacturing (AMM) program is getting ready to dive into its sixth year in fiscal year (FY) 2018 and has already begun to address key gaps within the nuclear manufacturing sector. Since its inception, the AMM program has awarded 27 projects through the Consolidated Innovative Nuclear Research (CINR) and Small Business Innovative Research (SBIR) solicitations to collaboration teams formed from 13 industrial companies, six national laboratories, and 14 universities.

Alison Hahn
U.S. Department of Energy

A key early award made to Purdue University, in partnership with Westinghouse Electric Corporation, successfully conducted the fundamental experimental and analytical work needed to develop the design specifications for Supplement No. 1 to the American Institute of Steel Construction (AISC) N690-15 for modular connection technologies used in steel-plate composite (SC) walls of Westinghouse's latest AP1000 reactors being built in the U.S. These standardized connection details and design guidelines will help to expedite the design, review, licensing, and construction processes for new nuclear reactors.

In another significant industrial collaboration, General Electric (GE) Global Research currently is investigating the use of near-net shaped, stainless steel components produced by direct metal laser melting (DMLM), which is an additive manufacturing technique, to accelerate the deployment of new and replacement nuclear components. GE Global Research has also partnered with the DOE Nuclear Science User Facilities (NSUF) to test these additively manufactured samples, fabricated at the GE Power Advanced Manufacturing Works facility in Greenville, SC, in the Advanced Test Reactor at the Idaho National Laboratory.

The AMM program is also sponsoring work with a number of U.S. manufacturers through the Electric Power Research Institute (EPRI) to demonstrate and test several new manufacturing and fabrication technologies with a goal of producing the critical assemblies of a two-thirds scale demonstration Small Modular Reactor (SMR) reactor pressure vessel (RPV). EPRI will work with a number of organizations to demonstrate six critical advanced manufacturing technologies with the ultimate objective of eliminating up to 40 percent from the cost to manufacture and fabricate an SMR RPV, while reducing the schedule by more than 18 months.

As the AMM program moves forward in FY 2018, the CINR solicitation (which can be found at neup.gov) will continue to be available to universities and national laboratories while the nuclear industry entities will be directed to submit proposals through an industry-focused solicitation currently being developed. The Department anticipates issuing this new funding opportunity announcement as early as the first quarter of FY18.

In This Issue

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

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Surface cladding and modification are extensively used in 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. Due to weldability issues, considerable challenges exist to apply new cladding materials by an arc welding process.

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 the metallurgical incomparability and poor weldability between the cladding materials and substrates, and the relatively low cladding productivity and high energy cost.

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

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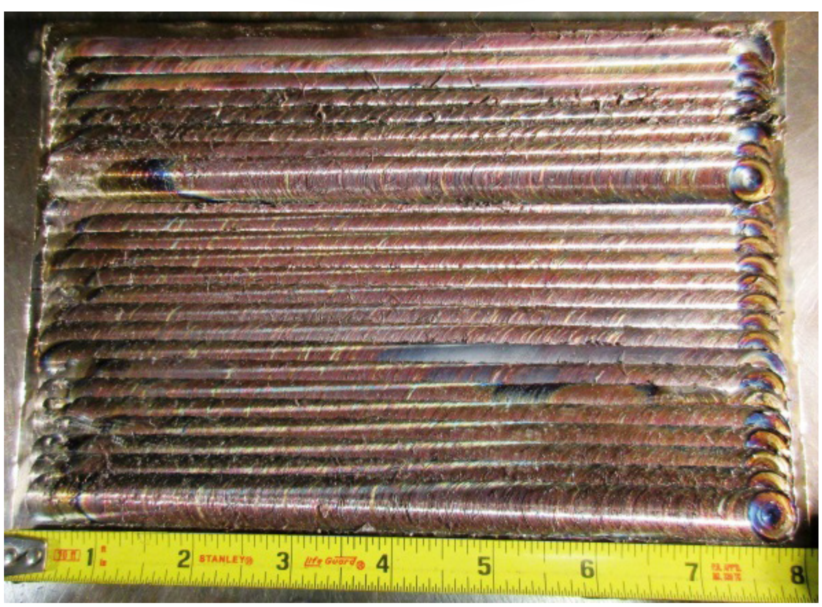

Figure 1. 304 SS piece cladded on A516 substrate by FSAM

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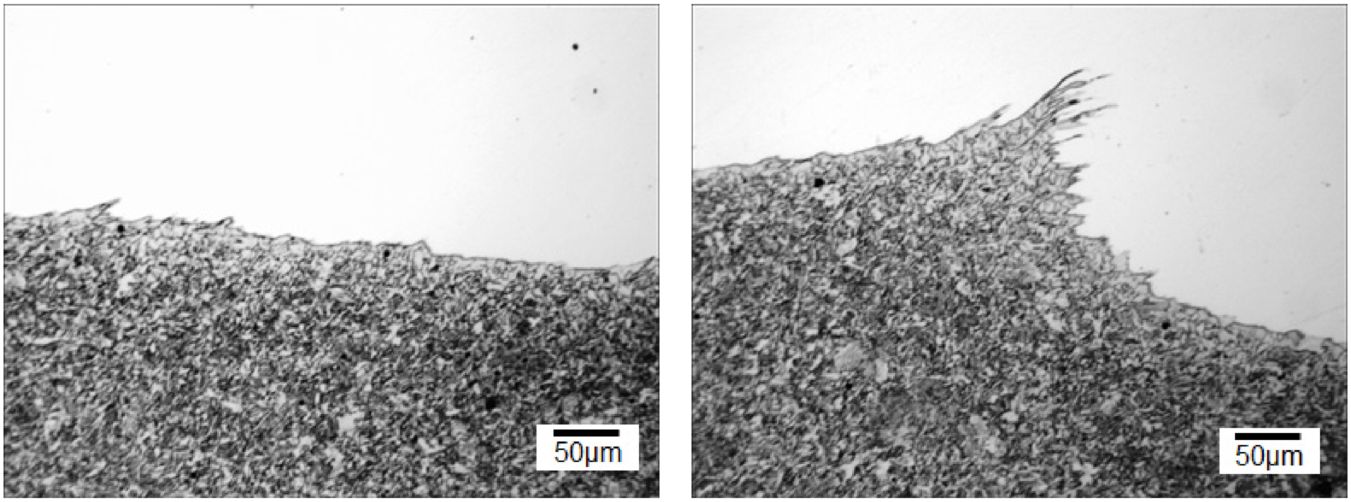

Figure 2. Bonded 304 SS and A516 PVS interface after FSAM

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

Since the start of the project in October 2016, we have demonstrated the feasibility of cladding layers of 304 stainless steel (304 SS) on A516 pressure vessel steel (PVS) substrate by FSAM. Figure 1 shows the cladded piece.

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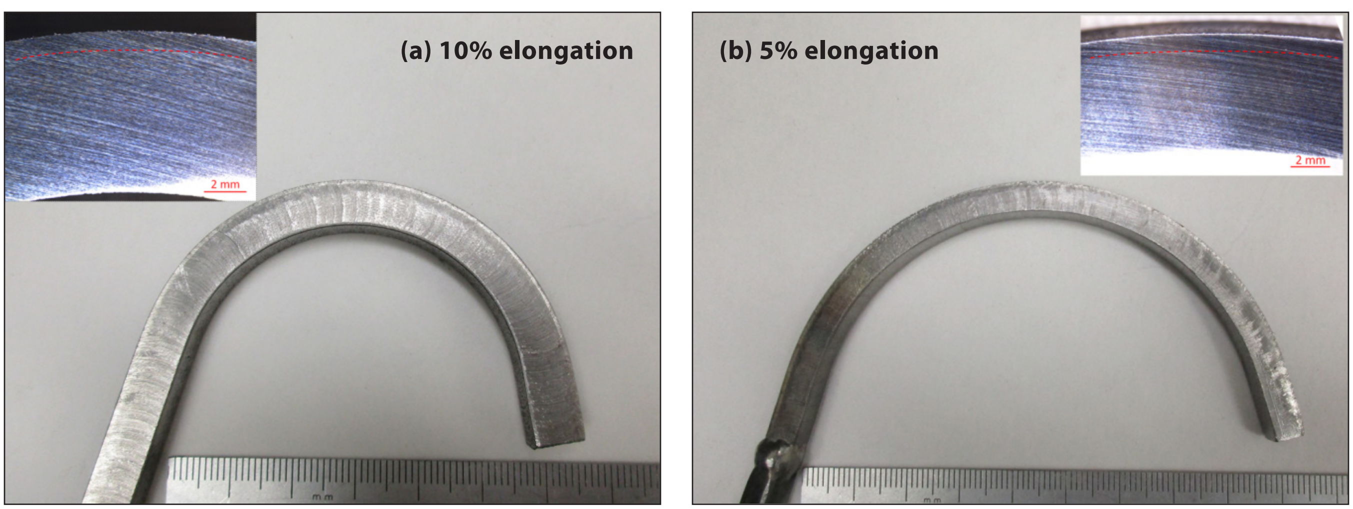

Figure 3. Mandrel bend test with different elongation at the FSAM interface

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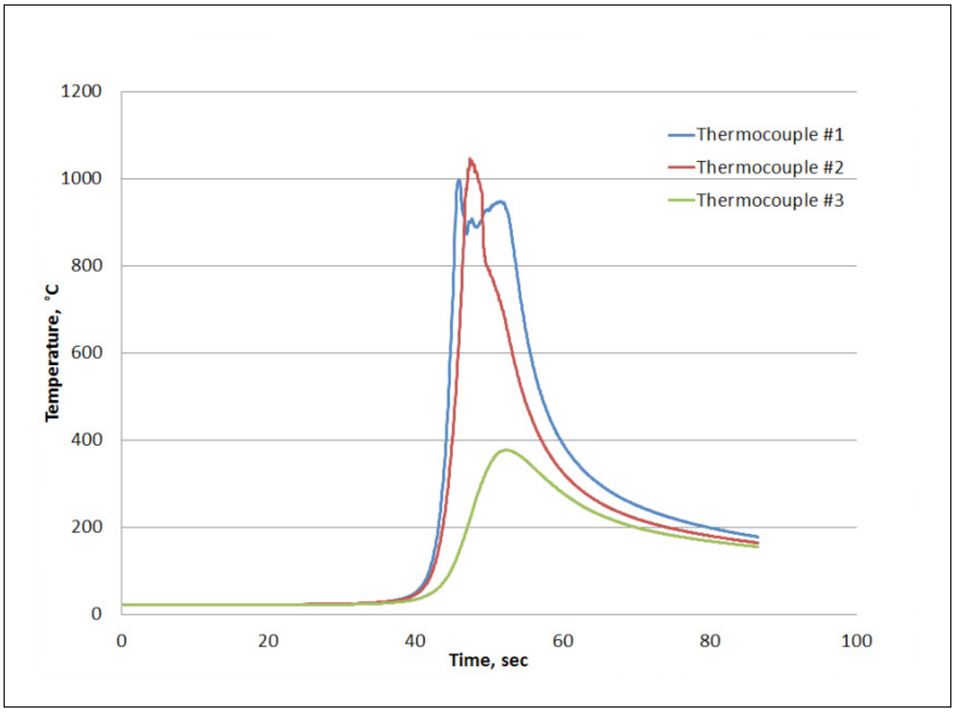

Figure 4. Mandrel bend test with different elongation at the FSAM interface

The influence of FSAM process parameters, especially the heat input of the process on interface bonding quality have been quantified. Suitable process window has been developed for the 304 SS to A516 steel combination. A metallographic examination clearly revealed well bonded interface between the 304 SS and A516 steel, as illustrated in Figure 2. The solid-state bonding quality was further tested by a bending test. In this test, the bonding line was subjected to 5 percent and 10 percent bending strain. Bent specimens and enlarged cross sections with interfaces are shown in Figure 3. There is no de-bonding or interface opening at the interfaces under both testing conditions.

Interface temperature was measured during FSAM. K type thermocouples were spot welded on the backside of the 304 SS through pre-drilled holes on the A516 substrate. Figure 4 shows examples of the thermal history at different locations during an FSAM cladding trial. The maximum measured temperature is 1045 °C, lower than the steel melting point of about 1370 °C.

Conclusion

The feasibility of cladding 304 SS onto A516 PVS substrate has been demonstrated. Both the metallographic work and bend test showed strong metallurgical bonding between the two materials when processing parameters were selected properly. Interface temperature measurement also confirmed that the FSAM is a solid state process, which benefits the dissimilar material cladding and modification in nuclear industry.

ICME and In-Process Monitoring for Rapid Qualification of Additive Manufacturing Components for Nuclear Applications

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Nuclear power plant equipment manufacturers have realized the potential to deploy additive manufacturing (AM) methods to produce reactor internal components due to the 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 often unconvinced about adopting these components for real-life service due to the scatter in metallurgical and mechanical properties emanating from machine specific and process variations, and thermal-mechanical signatures. Although current efforts to develop qualification standards are based on fabrication and testing of coupons, there is no clear, concise methodology for "component process-based" certification. For example, even when two identical parts are made with the same processing equipment and powder composition, variations in properties are observed due to stochastic variations in laser energy interaction and associated effects leading to inefficient melting and defect formation.

The current project will seek to assemble an innovative qualification strategy for complex nuclear components produced by laser powder bed (LPB-AM), which will be developed and demonstrated by leveraging relevant technology from emerging process analytics, high-performance computation models, in-situ monitoring, and big-data mining.

Tasks

The project scope consists of six tasks involving design, processing with in-situ monitoring, deployment of integrated computational materials engineering (ICME) models, ex-situ characterization, scale up of components, and compilation of methodology and data package for standards organization approval. The project scope starts with the design of a component with complex geometry and relevant to nuclear flow applications, using topology optimization methodologies for increased heat transfer efficiencies. Next, the component is produced in typical LPB-AM machines.

During the build process, in-situ process monitoring is performed with state-of-the-art infrared sensors. Some of the sacrificial samples, built at the same time during component manufacturing, will also be characterized using destructive ex-situ characterization techniques, including optical and electron microscopy. The ex-situ data is used to validate the computer algorithms for detection of defects from in-situ thermal and optical data, and microstructures and residual stresses predicted by computational models.

In the next step, all the defect and microstructural data with good spatial and temporal resolution is used within existing finite element methods to evaluate the expected static and dynamic performance of structures under service

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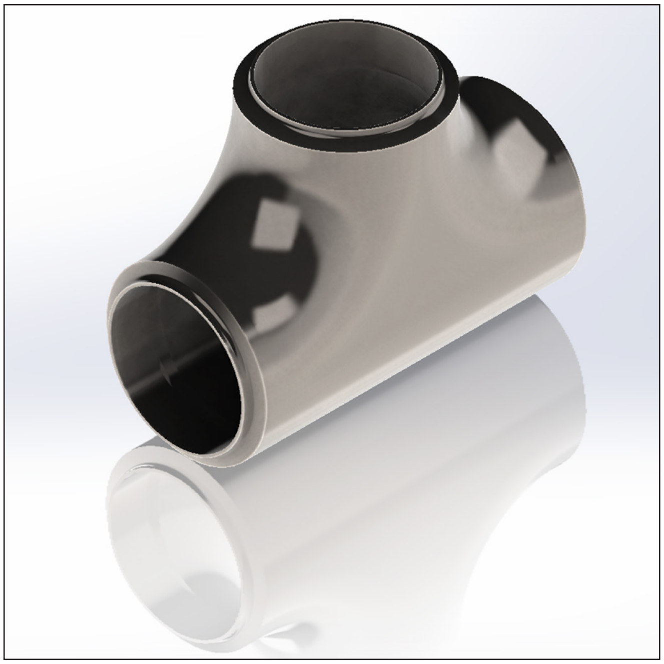

Figure 1. A 316L SS pipe tee fitting (128mm(L) x 6.4mm (T) x 0.49mm (dia)) is being produced via LPB-AM.

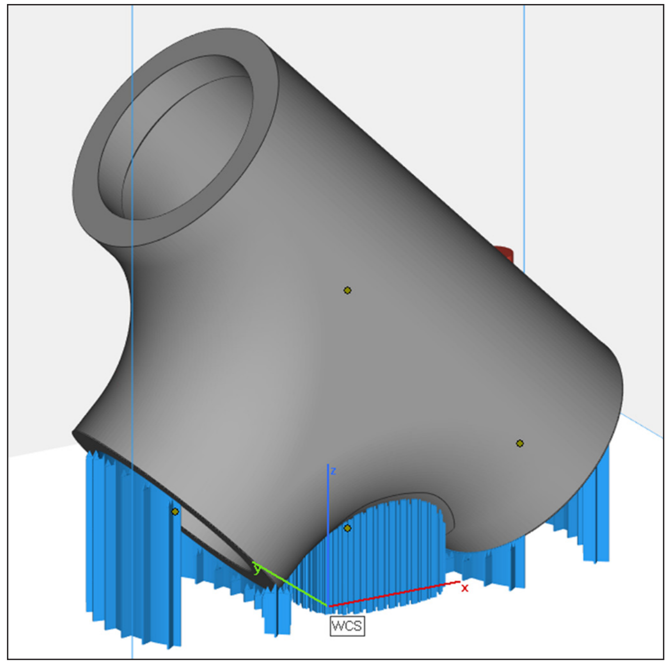

Figure 2. The pipe tee fitting is shown in a supported condition as it will be additively manufactured.

conditions. Finally, all the data from process parameter log files, in-situ and ex-situ characterization will be spliced together within a 3D data analyses framework. Although, each step of the objectives have been demonstrated individually, until now no one has integrated all the components to develop a live 3D data set that can be used as a qualification of additively manufactured components within the confines of American Society of Mechanical Engineers (ASME) boiler and pressure vessel codes.

Project Status

Much of the first six months of the project have focused on the development of laser powder process parameters and on selection and demonstration of infrared radiation (IR) thermal monitoring equipment which is being used by Oak Ridge National Laboratory to monitor the deposition process in real-time. A FLIR SC8200 IR thermal camera was selected based on its ability to identify very small defects (potentially on the order of 200 microns). Coupled with the Renishaw AM250 laser powder bed equipment, investigators have generated multiple 1-5 layer buildups (cylindrical coupons) wherein the IR camera was used to image on a layer-by-layer basis. Both random defect- and engineered-defect coupons have been generated and are being characterized in the project.

Key industrial partners (Rolls-Royce and Westinghouse) in the project have provided CAD models and geometries for two nuclear components that are being produced in the project. The first component is a small, Type 316L stainless steel pipe tee section (Figures 1-4), while the second is an Alloy 718 grid spacer. Over the next few months these small components will be produced using the LPB-AM process with and without defects, and will then be characterized using a wide range of metallographic techniques and computer-aided tomography (CT). Investigators will seek to develop a clear methodology for detection (and elimination) of defects in real-time during the application process.

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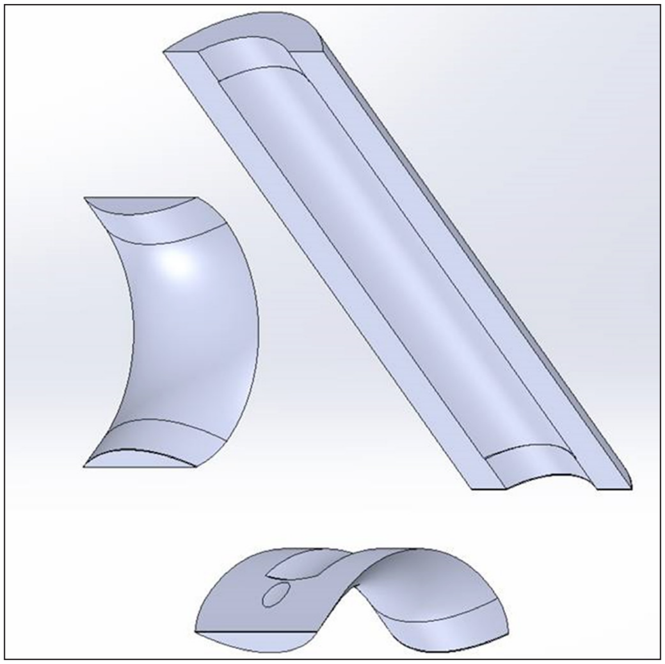

Figure 3. Critical sections of the 316L SS pipe tee fitting have been produced by LPB-AM for characterization.

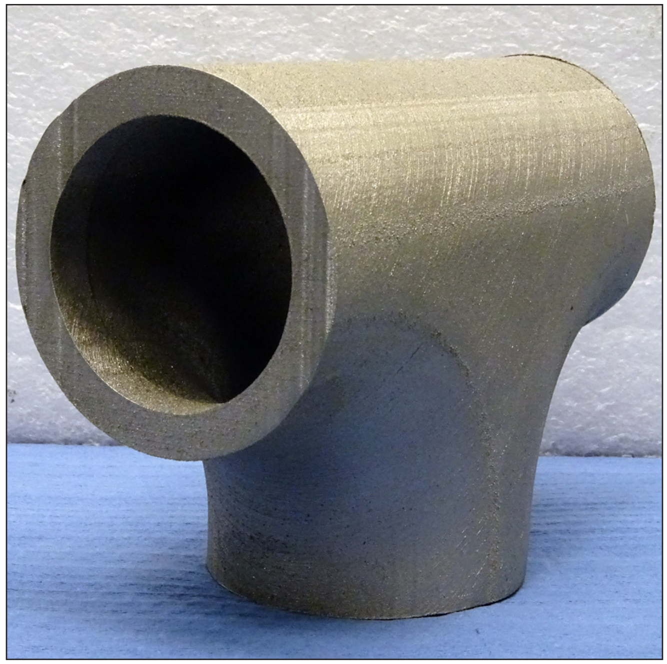

Figure 4. A 316L SS pipe tee fitting produced by LPB-AM.

Impact, Value, and Implications

The systematic qualification methodology and part certification developed in this project will allow for realization of the potential of AM, while providing manufacturers and regulators with component-level certification data. During this research, a flexible business and operational model will be initiated to allow for different vendors with state-of-the art ICME models, in-situ sensors and ex-situ characterization to work together.

Innovative manufacturing methods for nuclear applications are central to the NEET-1 program. Laser-based power bed 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 and approach to ensure nuclear grade quality can be met.

Acknowledgements

The principal investigators would like to recognize Dave Poole and Bryan Borradaile (Rolls-Royce) and Bill Cleary and Clint Armstrong (Westinghouse) who are providing key input and review into the LPB process development for nuclear applications.

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

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Advanced and additive manufacturing (AM) is expected to substantially reduce costs and deployment times of small modular reactors (SMRs). However, current electron beam systems for AM are limited in power and energy. Mainstream Engineering Corporation has commissioned a first-of-its-kind in the world of superconducting linear electron accelerators as a materials processing facility for novel AM. The superconducting linear accelerator enables materials processing at an electron beam energy of up to 1.5 MeV (25x higher than industrial electron AM systems) and at least 20x higher power at a comparable beam energy. This translates to deeper processing, faster additive build time, and unique far-from-equilibrium materials capabilities. More information of Mainstream's Electron Beam-Enabled Advanced Manufacturing (EBEAM) facility can be found at https://www.mainstream-engr.com/services/electron-beam-enabled-advanced-manufacturing/.

Mainstream will produce steel components for SMRs and other industries through its use of high-energy electron beam processing technology, and will demonstrate the ion radiation tolerance of AM. Mainstream will demonstrate the feasibility of AM of high-strength steel components through the production of sample coupons as well as compare microstructural and mechanical properties to conventional manufacturing. In addition, Mainstream will begin investigating microstructural and mechanical property changes from X-ray, gamma ray, and beta particle irradiation.

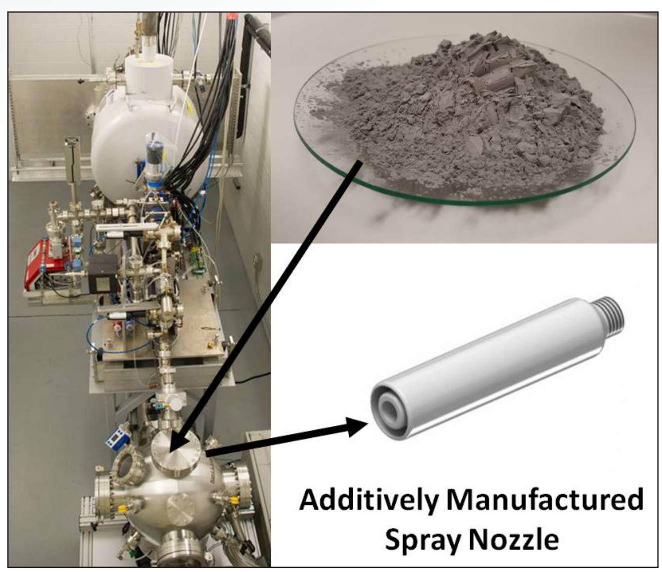

Figure 1. Additive manufacturing of steel components, such as spray nozzles, from powder for SMRs using Mainstream's high-energy, high-power EBEAM facility.

Additive Manufacturing of SMR Holddown Springs and Upper Nozzle Interface

Craig Gramlich
NovaTech

Additive manufacturing (i.e. 3D printing) has become a powerful tool in recent years. Much like the internet in the early 1990s, 3D printing has many untapped markets waiting to make use of this flexible technology. The nuclear industry is no different. Using 3D printing to increase performance and rapid prototyping of specific parts of nuclear fuel assemblies – the upper level components that contain fission fuel in nuclear reactors – an argument can be made to increase the percentage of additive manufacturing in nuclear fuel assemblies. In support of this objective, NovaTech has proposed to 3D print small modular reactor (SMR) holddown springs, which prevent the fuel assembly from lifting off the reactor core plate, and its upper nozzle interface. Using 3D printing to fabricate the holddown spring will allow for previously non-manufacturable geometries that will improve spring rate quality. In addition, computer aided design (CAD) of the holddown springs can be quickly verified by 3D printing many parts with subtle design changes, expediting testing. Swifter testing, cheaper mass-produced parts, and increased functionality for fuel assemblies and the nuclear industry is what 3D printing will bring; holddown springs are merely a starting point.

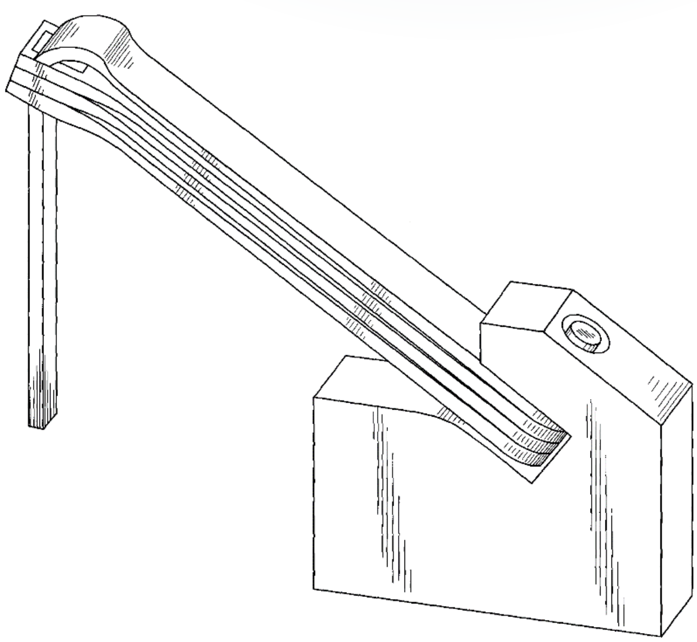

Figure 1. Standard holddown spring that can be improved with less parts, 3D printing, and CAD design.

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

George Pabis
NovaTech

With support from fuel fabrication partners, NovaTech looks to build on the success of its Small Business Innovative Research Phase I project into additively manufacturing (a.k.a. 3D printing) bottom nozzle and grid components for commercial nuclear fuel assemblies. In Phase I of this project, NovaTech successfully designed and prototyped multiple 5 X 5 arrays of bottom nozzle grillages utilizing Inconel 718 powder. The prototypes were tested for pressure drop performance, debris filtering effectiveness, and fuel rod capture feature strength. The test results showed that debris filtering could be successfully achieved over a broad range of pressure drops providing designers with the ability to "tune" the pressure drop of the bottom nozzle to achieve optimal performance. The fuel rod capture strengths exceeded expectations and showed that the bottom nozzle could be utilized to retain the fuel rods in a controlled geometry without the use of a bottom end grid.

Phase II work will focus on designing and fabricating a full-scale prototype bottom nozzle that will be flow tested to determine pressure drop performance as well as life and wear performance. Additionally, NovaTech is working with partners to develop 3D printed Inconel 718 samples that can be neutron irradiated to determine irradiation effects on 3D printed material properties.

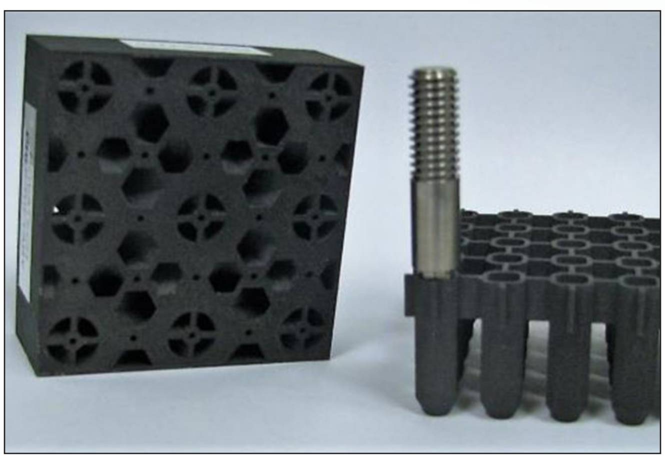

Figure 1. Prototype 5X5 Bottom Nozzle Grillage Arrays

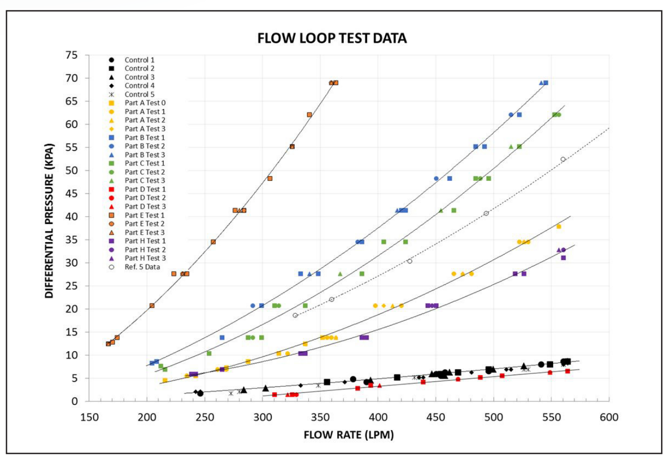

Figure 2. Flow Loop Test Data

To submit information or suggestions, contact
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