AMM Newsletter

Advanced Methods for Manufacturing

Issue 11 • April 2020

Dirk Cairns-Gillamore Joins AMM Program

Dirk Cairns-Gallimore has joined the Advanced Methods for Manufacturing team as the DOE-NE headquarters program manager. Cairns-Gallimore is a native of the Pacific Northwest. He graduated in 2001 from Oregon State University with a degree in nuclear engineering and started his career in 2002 in the Department of Energy's Office of Nuclear Energy, working in the Office of Space and Defense Power Systems. Over the course of 18 years, he was program manager for the multi-mission thermoelectric generator (MMRTG) that was used on Curiosity Rover and will power the upcoming Mars 2020 mission of the Perseverance Rover. He was also the NE-headquarters manager for the activities at the Space and Security Power Systems Facility at INL during the fueling of the General Purpose Heat Source—Radioisotope Thermoelectric Generator (GPHS RTG) for the New Horizons mission to Pluto. Prior to joining the AMM program, he spent a year on detail with the U.S. Coast Guard at their headquarters in Anacostia, Virginia. There he helped further enhance and integrate the Coast Guard's enterprise risk-management system across 23 organizations.

Dirk Cairns-Gillamore
DOE-NE program manager

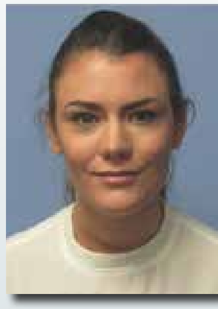
Mr. Cairns-Gallimore brings an interesting perspective to the program. Through his work with space and defense, he was able to be part of a program that integrated expertise from private industry, academia, the national labs, and multiple agencies into mission-critical, time-sensitive product delivery. The production of an RTG is complex, an interdisciplinary engineering process that requires knowledge of manufacturing and fabrication processes, including welding, chemistry, and materials science (including, e.g., ccarbon-carbon composites, aluminum, and iridium). Cairns-Gallimore's experience gained during the production of MMRTGs is germane to many of the processes involved in the AMM program: ball milling, powder metallurgy, hot isostatic pressing, and welding processes, including thermogravimetric analysis , laser and e-beam welding, and others. This background is crucial to the expansion of research and development towards commercial deployment of advanced manufacturing, in accordance with ASME NQA-1 standards.

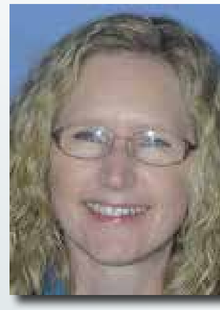
Mr. Cairns-Gallimore is an ardent supporter of deploying AMM processes for use by the nuclear industry. He believes that it will be critical for the continued success of both the current reactor fleet and future investment in advance reactors. His time at the Coast Guard reemphasized the power of teamwork and showed that the focus of a determined group of people can create success despite a challenging environment. One of his main goals for the program is to establish priorities for materials and processes so that AMM can be deployed for first-of-a-kind uses. The ability of the AMM community to come together and push toward this goal will determine its success.

In This Issue

U.S. DEPARTMENT OF ENERGY

Technical Review Webinar and Survey Summary





Isabella van Rooyen
AMM National Technical Director

Sarah Roberts
AMM Program Administrative Assistant

Darcie Martinson
Systems Engineer

The annual AMM Program Technical Review Meeting was held December 17-18, 2019, in the form of a webinar. Over the two-day period, 37 people participated in the meeting. Presentations were made on 17 currently funded projects initiated between FY 2016 and FY 2019. Each PI addressed their project's objectives, team, plan and status including milestones, risks, highlights and successes. In addition, publications, presentations and next activities were discussed. A question and answer session was held after each presentation. Webinar participants typed in and submitted their questions which were then answered by the PIs. Presentations from the meeting are posted on the Nuclear Energy Enabling Technologies (NEET) Crosscut Advanced Methods for Manufacturing Website and can be found at the following link: https://www.energy.gov/ne/listings/neet-documents

To seek feedback on the technical review meeting and gather input on future strategy of the AMM program, a survey was distributed to 115 stakeholders. Survey responses were received from 31 people, with a 27% participation rate. Survey respondents included representatives in the following roles: Principle Investigators (PIs) and co-PIs, Department of Energy (DOE), industry, project researchers and others (e.g., potential project participants, national technical directors, and regulatory support). The outcome of this survey played a crucial role in the drafting of the preliminary AMM program's strategic plan. Selected results are provided below with more detailed results available upon request.

Questions regarding Technical Review Meeting/Webinar

Location/Platform: For the next annual AMM program technical review meeting, 54% of the respondents favored a face-to-face meeting, while 46% preferred a webinar. However, when broken down by type of respondent, PIs and co-PIs slightly preferred a face-to-face meeting (58% preferred face-to-face, 42% preferred a webinar). If the next technical review meeting is in person, recommendations for the location included Washington, D.C. (recommended by 8 respondents) or a national lab (6 respondents). Other responses included universities, an AMM facility, EPRI, OEM, research sites, and an industrial facility with novel equipment to support a tour. Respondents recommended that the meeting be held in a central location near a hub airport with reasonable airfare, good airline connections and access to reasonable hotel rates.

Active Participation: A variety of ways were identified for actively participating in the next technical review meeting and these included:

1. Identifying crosscutting opportunities for collaboration and learning about technology development that might be useful to other programs
2. Networking with other researchers and participating in breakout sessions
3. Reviewing projects/presentations prior to the meeting in order to ask informed questions
4. Providing briefings on and identifying needs and technical gaps for particular programs and industry that could use AMM technology and research.
5. Learning about technologies that might be useful to particular programs (e.g., Microreactor Program)
6. Understanding and closely coordinating with AMM program activities to support the successful approval/licensing of developing AMM techniques

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Breakout Sessions: When queried about whether breakout sessions should be held on particular topics during the technical review meeting, 70% of respondents agreed that they would be useful. Breakout session topics suggestions included status of existing efforts to qualify or approve developing methods for commercial use; codes and standards and alternative qualifying approaches; modeling and simulation; cladding; PM-HIP; materials development; AMM and NEET program; additive manufacturing high entropy alloys; advances in additive manufacturing; SMRs; and cost-competitiveness with traditional manufacturing techniques.

Overall Recommendations: Ideas for improving the effectiveness of the technical review meeting included clarity regarding how the meeting ties to future calls/proposals, assuring that PIs are focused on the research bottom line (value of the outcome to DOE goals), and enhancing networking opportunities.

Questions regarding AMM Program

Improving Collaboration: To improve collaboration between PIs, recommendations centered around offering more networking opportunities at workshops or conferences, establishing quarterly conference calls, and providing funding or financial incentives. In addition, prior to the technical review meeting, a contact list with bios could be distributed with a list of the presentations so contacts could be made in advance of the meeting by the individual PIs. The observation was made that collaborations should be organic through networks that is formed or identified as a result of the AMM program's activities or other preferences.

Improving collaboration between PIs and industry included ensuring AMM projects have outcomes that are connected with industry needs, inviting relevant industry entities to the annual technical review meeting or other AMM workshops/conferences, providing better face-to-face networking opportunities, providing funding and/or financial incentives, increasing the frequency of technical communications with PIs, defining specific and quantifiable contributions from industry, involving industry in quarterly teleconferences with NTDs and PIs and arranging for PIs to present to small, mid-sized and large nuclear companies. A participant expressed the need that facilitation between PIs and Industry should increase to enable better understanding of the "bigger picture" for research needs.

Initiatives: Specific initiatives and other areas the AMM program could learn from, benefit from or integrate with in the future included the Microreactor Program, NASA Marshall Research Center (most advanced in terms of establishing qualification standards for additive manufacturing), GAIN, and programs supported by ARPA-E and EERE.

Impact: To increase the AMM program's impact in the nuclear energy industry, respondents' suggestions included ensuring that AMM is focused on high priority, high impact research that addresses nuclear needs (e.g., speed to market with zero mistakes and a set of data to prove it, making more fuel available for SMRs sooner) and has a clear path to adoption; providing incentives for utilities and vendors to work with PIs on new technologies; closely evaluating projects submitted by the universities to ensure they have an industrial co-sponsor or have industry engagement and can envision a way to deploy the technology; and extending technical review meeting invitations to representatives from the nuclear energy industry, nuclear commercial reactor developers and other industries who may be helped by the technologies being presented to the technical review meeting.

Conclusion: In summary, the survey provided insightful recommendations which will enhance future AMM program technical review meetings and strategy. As a result of the survey, the following actions are being taken by the AMM program team:

- Improve guidance and interaction with PIs by
  - o Enhancing guidance on developing milestones to be used in quarterly reports as well as improved descriptiveness of feedback on progress or potential issues
  - o Exploring options for best means of implementing effective quarterly communications with PIs and Co-PIs to provide more direct feedback from the AMM National Technical Director and DOE
  - o Enhancement of PI-stakeholder collaboration will be enabled and facilitated during AMM program initiatives like open technical review meetings, newsletters among other. Visibility of current awards and the progress will further increase the impact of the research and development work in other DOE-NE programs."
- Make a final decision (around the September 2020 timeframe for format and location of AMM Program Technical Review Meeting (may be dependent on COVID-19 pandemic guidelines at the time)
- Continue to utilize survey responses to inform development of the draft AMM program strategic plan.

AMM program representatives at the February 2020 Paris GIF workshop organized by the AMME task force

Generation IV International Forum (GIF) is a multilateral framework to conduct collaborative research and development that is needed to ensure feasibility and performance capabilities for the next generation of nuclear energy systems.

Advanced Methods for Manufacturing (AMM) National Technical Director, Isabella van Rooyen, as the US Representative for the GIF Advanced Manufacturing Materials Engineering (AMME) Task Force, presented at the 2020 GIF Workshop on Advanced Manufacturing, held in Paris, France, February 18-20, 2020. In addition to the three presentations given by Dr. Isabella van Rooyen/Dr. Mark Messner, Dr. Kurt Terrani and Dr. Dave Gandy, Dr. Mark Messner (co-chair of AMME taskforce) and Dr. Isabella van Rooyen, as AMME taskforce members, were assigned to lead multi-disciplinary workshop breakout sessions. The outcome summary for this workshop will be reported in the September 2020 newsletter.

The GIF AMME Task Force was established when GIF was faced with the acknowledgement that developments in advanced manufacturing are occurring much faster than the ability to introduce new materials and methods into design codes. This potentially stifles innovation and hampers deployment. Also, getting new materials or new manufacturing processes qualified to be used in nuclear design codes can be extremely timely. If Gen IV reactors are to be brought to the market in a reasonable timeframe, these concerns must be addressed.

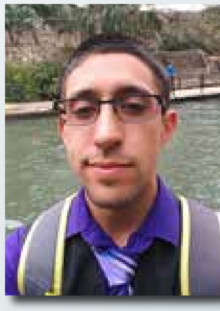
The objectives of the GIF AMME Task Force and associated workshop, are:

- Assess interest of research institutions and nuclear companies within GIF in crosscutting activity, which will support Advanced Materials and Manufacturing solutions to a High Technology Readiness Level (TRL).
- Develop and apply a flexible and accessible approach with clearly identified mechanisms for directly involving leading and SME advanced nuclear reactor companies from GIF countries.
- Develop a priority list of R&D areas and initiatives.
- Interact with the GIF Technical Secretariat to make use of its services and capabilities, including any use of the GIF IT infrastructure.
- Deliver a white paper discussing the identified merits and difficulties of such cooperation on this topic and identifying potential ways forward.

From left to right: Dr. Kurt Terrani (ORNL), Dr. David Gandy (EPRI), Dr. Mark Messner (ANL), Dr. Isabella van Rooyen (INL)

DOE PROGRAM OUTREACH

Additive Manufacturing of Microreactor Component Test Articles

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DOE's Microreactor Program develops capabilities to perform thermal and integrated-systems testing by establishing the Microreactor Agile Non-Nuclear Experimental Testbed (MAGNET). This test bed will allow a range of experiments for heat-pipe and gas- and liquid-cooled microreactors. Additive manufacturing is one fabrication technology being explored to produce components for MAGNET. Metal additive manufacturing is a developing technology allowing freedom of design in short time frames for complex designs that are difficult to fabricate with conventional machining. The test articles shown in Figure 1 and fabricated for the Microreactor Program are examples of how additive manufacturing can be used for MAGNET.

This article describes experimental methods and initial results of the fabrication of two stainless steel 316L test-article designs. The first comprises seven holes in a hexagonal geometry to represent a simplified monolith: one central hole for a heat pipe and six surrounding holes for heaters to simulate heat from fuel rods. Parts were fabricated at 280 mm long. The second article comprises 91 holes, also in a hexagonal geometry: 37 for heat pipes and 54 for heaters, with a maximum height of 292 mm.

Experimental Method

To produce the components, the team utilized both M290 and M400-4 machines built by Electro-Optical Systems (EOS), Inc. Both machines are laser powder-bed fusion instruments that produce components by melting thin layers of powder together into final- or near-final-dimension components. The M290 has a 250 mm × 250 mm build bed that allows for the manufacture of a 150 mm tall, 37-heat-pipe, reactor-core block components. The M400-4 has a 400 mm × 400 mm build area and was used to produce multiple 7-hole components up to 280 mm tall as well as two 37-heat-pipe components up to 292 mm tall, simultaneously. In addition, arrays of tensile bars serving witness coupons

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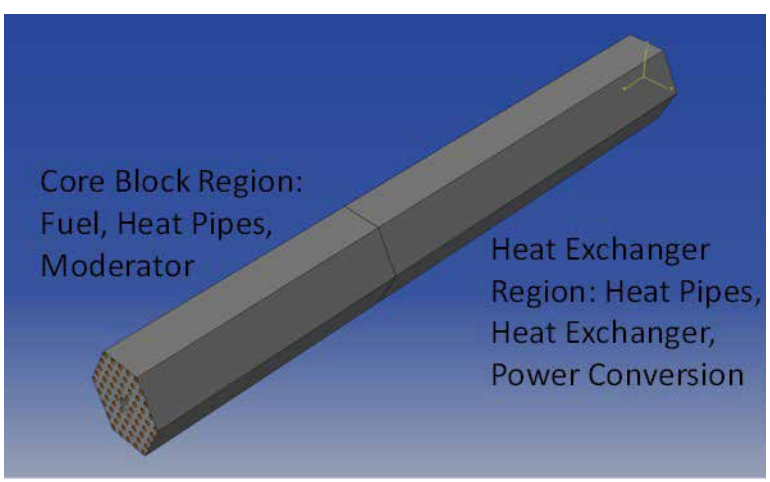

Figure 1. Example monolith geometry that comprises heat pipes to transfer the thermal energy generated during fission in the fuel to a heat exchanger and a power-conversion unit. The core block, with both fuel and heat pipes, is in one half, and heat pipes and a heat exchanger are in the other.

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were fabricated simultaneously for material-quality and mechanical-property studies. All components used the default EOS DirectPart parameters designed for 316L stainless steel. The 7-hole components took an average of 2–3 days per build, and four were fabricated at the same time (see Figure 2a). It took 26 days to build a pair of 292-mm-tall, 37-heat-pipe components (see Figure 2b). In both cases, a single laser was used to manufacture each individual part. Analysis is currently underway of the 37-heat-pipe components, but the focus of this article is on lessons learned during fabrication of the 7-hole article.

The initial core-block samples for both the 7-hole and 37-heat-pipe designs were produced by taking a Solidworks design file and converting it into high-resolution stereolithography (STL) format. STL file format is based on triangulation, which results in a representation of all geometries, including circles, as a series of angular edges. High resolution is required to produce effectively an accurate representation of a circular geometry. This inherent limitation in input-file format means that if a sufficiently high resolution is not used, some post-fabrication machining will be necessary to achieve the tight tolerances for the holes. After each build, the parts were heat-treated at 900ºC in a vacuum for times dependent on overall part volume to relax residual stresses inherent to the build process.

Results and Discussion

The initial set of 7-hole components exhibited tapering in the holes—with an accurate hole size at the bottom of the fabricated piece and a narrower hole at the top—due to residual stress. To visualize the taper, Figures 3a and 3b show that the hole size narrowed as it moved upward through the build geometry and did not meet desired tolerances. The holes were not uniformly distorted: the center hole was less distorted than the outer holes, and the centers deviated by <100 µm. This phenomenon is a result of residual stress and was not recoverable with post-build heat treatments.

Post-fabrication machining with wire electrical discharge machining (EDM) was employed to repair the part in order to meet specifications. However, the 280 mm length of the hole created challenges for post-fabrication machining. EDM relies on a wire and, over the length of the part, was not able to hold the tight tolerances needed. Post-machining inspection with pin gauges indicated a successful fix of the initial part; however, further measurements with a boroscope showed that the holes in the middle of the part expanded in size by 150–200 µm. This expansion was a result of normal wire bending and is inherent to the EDM process for long-length cuts. Thus, the part had to be refabricated to be more accurate and meet tolerances without post-machining. The wire-EDM samples also revealed that the parts did not have sufficiently high resolution, and triangulation was evident within the bores. Further iterations with higher-resolution STL combatted this issue.

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Figure 2. (a) Four 280 mm tall 7-hole test articles on the build plate and (b) two 292-mm-tall 37-heat pipe test articles on the build plate.

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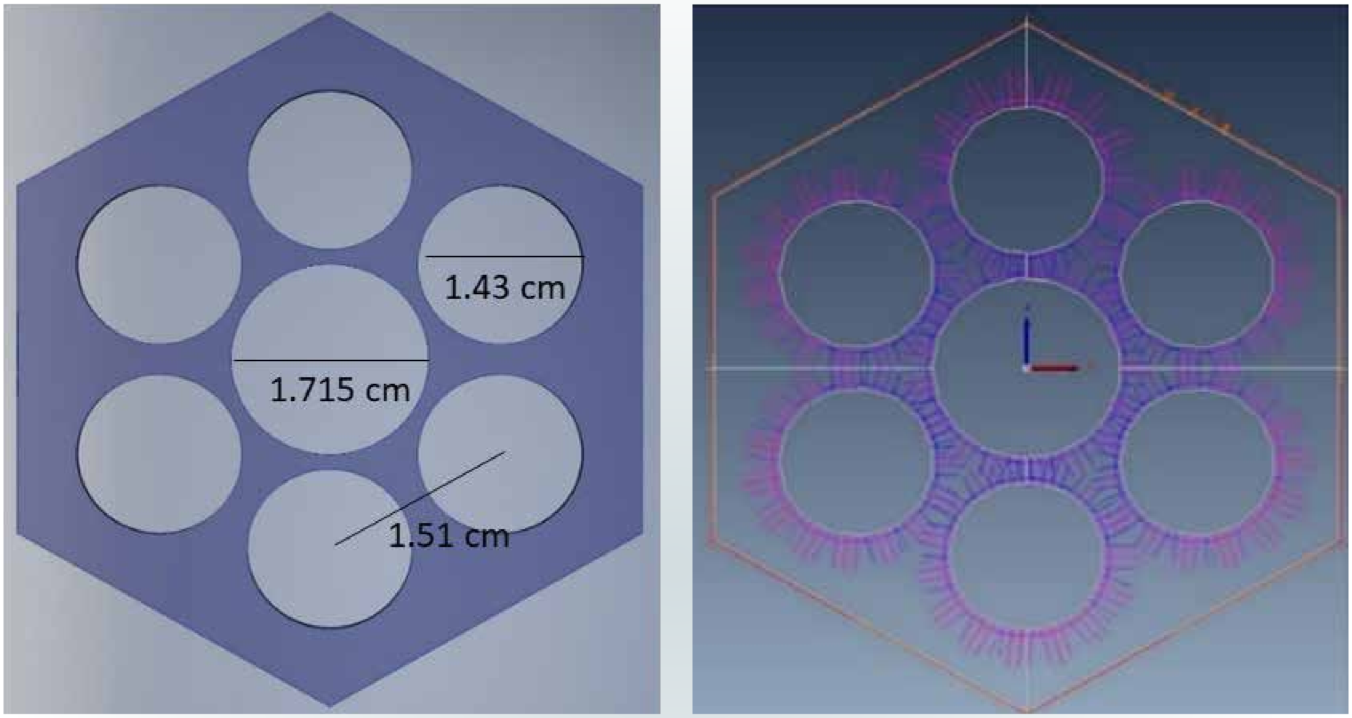

Figure 3. Seven-hole test article drawing designed for compensation, showing (a) taper from top to bottom and (b) deviation of a compensated 7-hole test article model as drawn.

To compensate for taper distortion, an inversely distorted model, with compensated hole sizes, was created so that any shrinkage that occurred would cause the component to self-correct into the desired straight geometry. An image of the inversely-tapered model is shown in Figure 3b, which can be contrasted with Figure 3a. This model was made by taking the measured values at the top of the initial, tapered 7-hole built pieces and multiplying them by a scaling factor. This scaling factor was the drawing's original dimensional value, divided by the actual built value. There was a slightly different scaling factor for every dimension, so the compensated model was only consistent radially and not straight on any axis. The relatively simple geometry of the 7-hole block made hand calculations possible without complex stress modeling. This inversely tapered model was then built, and the holes in the resulting part had improved straightness, allowing the part to meet the required tolerances.

In summary, the compensated 7-hole design was produced by measuring the dimensions (hole size and placement, as well as exterior dimensions) at the top and the bottom of the part. These measurements were then compared to the ground-truth of the desired model. The difference between the two informed the required taper for a model that would shrink to the correct dimensions. The final set of test articles were produced within the required 50 μm tolerance in position and straightness.

Conclusions and Future Work

Through additive manufacturing, this research successfully produced 280-mm-tall components for non-nuclear test articles for the Microreactor Program with accuracy and fidelity. The compensated components met 50 μm tolerances using a simple compensation method. For more-complex geometries than those explored here, simple compensation might not be possible without improved tools, necessitating post-fabrication machining, but utilization of stress-simulation software could result in the required compensation patterns. Further reduction of the taper and hole sizes, such as through undersizing of holes could allow for wire-EDM finishing to create a straight hole without taper. This method could be explored in the future. Additive manufacturing is a developing technology and poses challenges in machine reliability, but with new machines and tools always on the market, the future should be bright for meeting requirements for future designs.

Acknowledgement

This work was supported by the U.S. Department of Energy, Office of Nuclear Energy's Microreactor Program.

AMM FUNDED PROJECTS

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 its unique capability to generate complex geometries rapidly and to improve its overall cost. At the same time, Code and regulatory bodies are often unconvinced about adopting these components for real-life service applications 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 F42) are based on fabrication/testing of coupons, there is no clear, concise methodology for "component process-based" certification. For example, even when two identical parts are made with 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 seeks to: (1) assemble an innovative qualification strategy for complex nuclear components produced by laser powder bed (LPB-AM), and (2) leverage relevant technology from emerging process analytics, high-performance computation models, in-situ monitoring, and big-data mining.

Tasks

The project consists of six tasks involving design, processing with in-situ monitoring, deploying integrated computational materials engineering (ICME) models, providing ex-situ characterization, scaling up components, and compiling methodology and data package for standards organization approval. The project scope starts with design of a component with complex geometry, 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 detecting defects from in-situ thermal and optical data and microstructures and residual stresses predicted by computational models.

In the next step, the defect and microstructural data are used within existing finite element methods to evaluate the expected static and dynamic performance of structures under service conditions. Finally, the data from process parameter log files and in-situ and ex-situ characterization are to be spliced together within a three-dimensional (3-D) data analyses framework. Although each step of the objectives has been demonstrated individually, until now no one has integrated all of the components to develop a live 3-D data set that can be used as a qualification of additively manufactured components within the confines of ASME boiler and pressure vessel codes.

Project Status

Metallic components with complex geometries relevant to nuclear power applications can be designed and produced with LPB-AM additive manufacturing processes. In this project, in-situ optical monitoring and image analyses were assessed as potential industrial tools for evaluating the porosity distribution in AM components. A methodology was developed by the research team that was able to provide quantitative 3-D information of defects/porosities within the build parts. Its effectiveness was verified

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with ex-situ computer-aided X-ray tomography and the technology was subsequently transferred to industrial participants for use within their respective AM systems.

In-situ infrared (IR) image collection and analyses in simple cubic geometries (Ti_6Al_4V) and in complex geometries (316L SS) with engineered defects showed that thermal signatures correlated extremely well with the actual location of the defects. Using this technology, it was demonstrated that variations of IR signals could be readily extracted as a function of time and location. The spatial and temporal resolution associated with these defects are dictated by the IR camera and recording hardware employed. The analyses showed that thermal signatures are strongly affected by the processing parameters (e.g., laser power and velocity), scanning strategy (direction, orientation, and length), and the evolving geometry of the part with the progress of the printing. However, the industrial deployment of such IR-based tools for qualification of AM was found to be impractical due to (1) the need for large storage media, (2) the lack of computational tools for analysis, and (3) the time required to process the real-time data. As a result, the team began to explore in-situ optical imaging methods to assess defect development during component builds.

To understand the relationships of defects on component properties in the as-built and post-process HIP conditions, tensile samples with engineered defects/porosities (200, 250, and 500-μm sizes) and different volume percentage (1%, 3%, and 5%) were produced successfully and the defect locations were confirmed using in-situ optical imaging and computer-aided X-ray tomography. These engineered defects were attributed to the scatter in the total elongation during tensile testing. The scatter in tensile properties was reduced with the application of hot isostatic pressing (HIP) that is followed by a solution anneal and quenching heat treatment. The research demonstrated that by using HIP, the scatter in 316L steel AM properties within single and complex components with porosity introduced can be minimized and one can meet the expected properties outlined in standards.

In another part of the study, ICME process-microstructure modelling shows that spatial variations of thermal signature (thermal gradient and liquid-solid interface velocity) during L-PBF process (i.e., within our processing conditions) may not lead to any non-equilibrium solidification. Although, the ICME microstructure-defect-property modeling confirms that the spatial distribution of porosity may lead to local stress/strain concentrations during mechanical testing. Comprehensive prediction of the stress-strain constitutive properties at nm- to μm-length scales are beyond the scope of commercially available computational finite element models and should become part of the future research.

In yet another part of the study, three AM components were built and rigorously evaluated via mechanical testing and microscopic examination. The results of the testing were used to assemble an ASME data package that will be used to support an ASME BPV Code Case for 316L SS components produced by LPM-AM. Five different organizations (Westinghouse, Rolls-Royce, ORNL, Auburn University, and Oerlikon) were asked to produce AM components. Examples of two of the component-builds are shown Figures 1a and 1b, along with an example of the sample removal that was utilized (Figure 2). It is anticipated that the Code Case will be submitted in Q4-2020.

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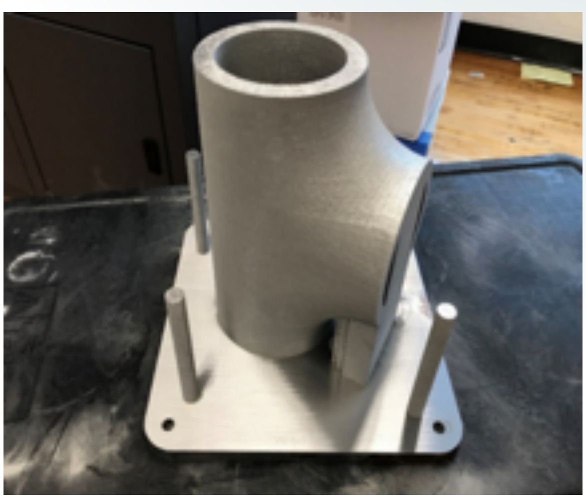

Figure 1a. A 316L SS Pipe Tee fitting is being produced via LPB-AM.

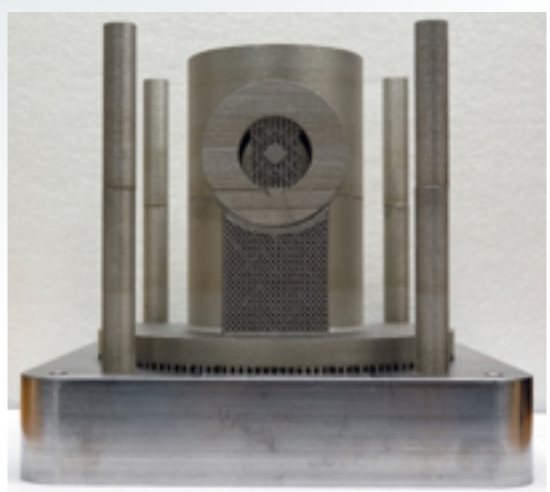

Figure 1b. A 316L SS section of a valve body was produced via LPB-AM.

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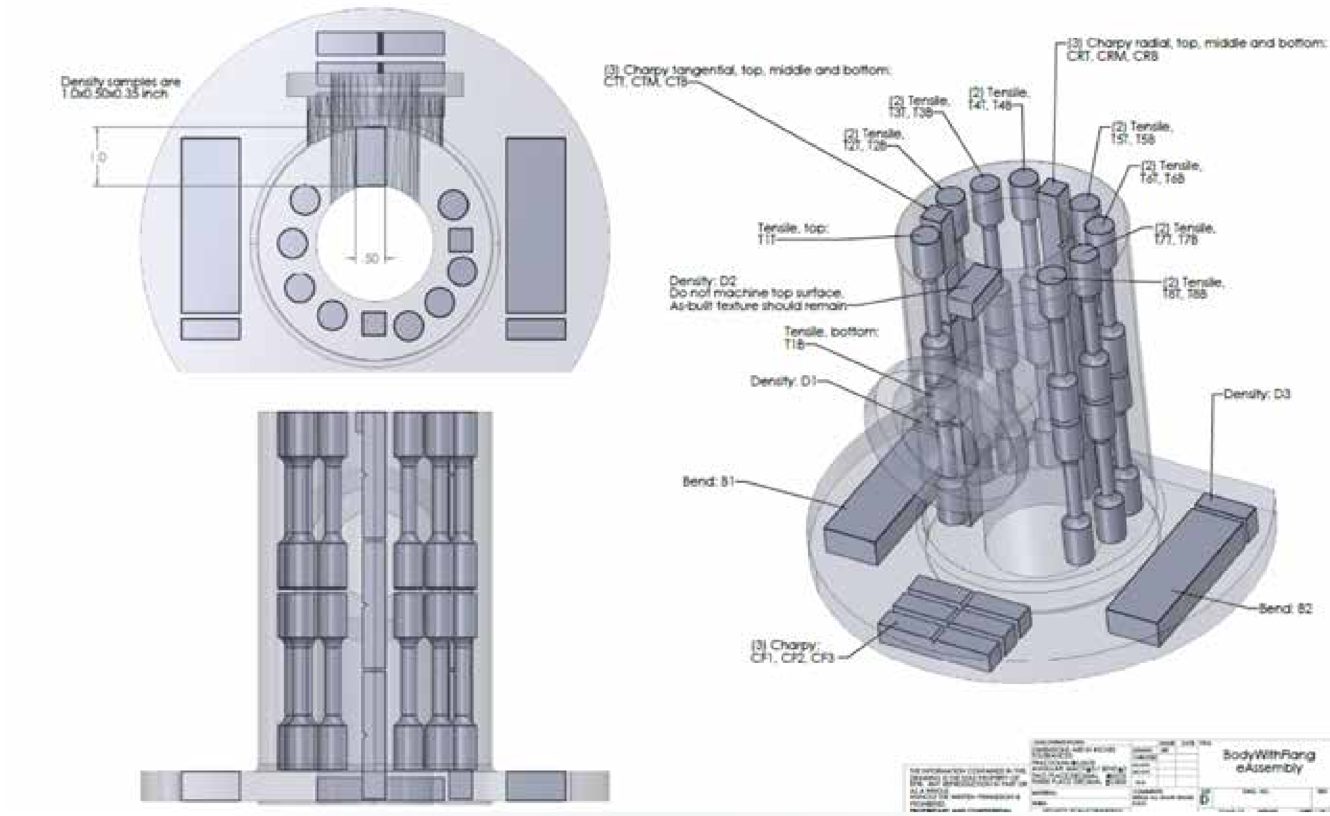

Figure 2. Sample removal included tensile, bends, and Charpy impact toughness coupons.

Impact, Value, and Implications

The systematic qualification approach, part qualification and certification developed in this project will allow for realization of the potential of AM, while providing manufacturers and regulators with component-level certification data. Innovative manufacturing methods for nuclear applications are central to the AMM 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/approach to assure nuclear grade quality can be met.

Acknowledgements

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

Towards Intelligent Laser 3-D Manufacturing System

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The next generation small modular reactor requires new and improved techniques, instrumentation, and strategies to deal with the anticipated high-radiation and high-temperature environment (esp. in reactors). Component manufacturing technologies will be required that take full advantage of the new three-dimensional (3-D) printing methods employed by additive manufacturing technologies. These manufacturing methods must be capable of producing components or subcomponents on a limited production basis and with nuclear quality.

Based on our success in developing a variety of award-winning high-energy and high-power ultrafast fiber lasers and our pioneering work in fs laser 3-D manufacturing (U.S. patents 9643361 and 9770760), PolarOnyx is developing an intelligent additive manufacturing (AM) and subtractive manufacturing (SM) system to make nuclear quality components for small modular reactors. This all-in-one multi-functional capability (SM and AM, controllable laser energy/power, controllable melt temperature) will significantly reduce building times and qualification costs to a degree not achievable by conventional laser AM machines. By integrating these features with fs laser SM, layer-by-layer processing can be done to micron-level precision so that complex shapes with fine structures are achievable.

The experimental setup has been modified based on the existing powder bed AM and SM facilities in the application laboratory of PolarOnyx. It mainly comprises a tunable pulsed fiber laser system, beam delivery components, a beam shaper to form desired shapes (flat top, donuts), an automated motion system, a scanning system, a powder delivery system, and a control system. The laser beam is reflected by mirrors and focused by a lens towards the sample. An acoustic-optic (AO) modulator is used to optimize the laser power and format for the melt pool temperature control. A mechanical shutter is also synchronized with the laser system for safety. An Non-Destructive Inspection (NDI) system, which is an essential part, is assembled to the powder bed system (Figure 1) to provide real-time and in situ surface characterization

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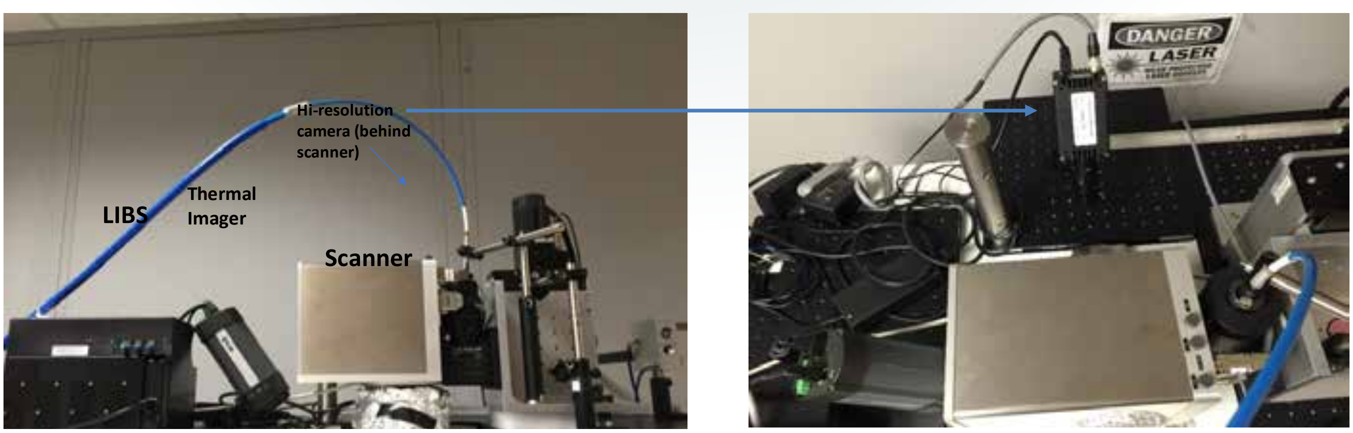

Figure 1. Experimental setup of the controllable laser 3D manufacturing system.

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Bright/dark pixel ratio is directly correlated to surface roughness

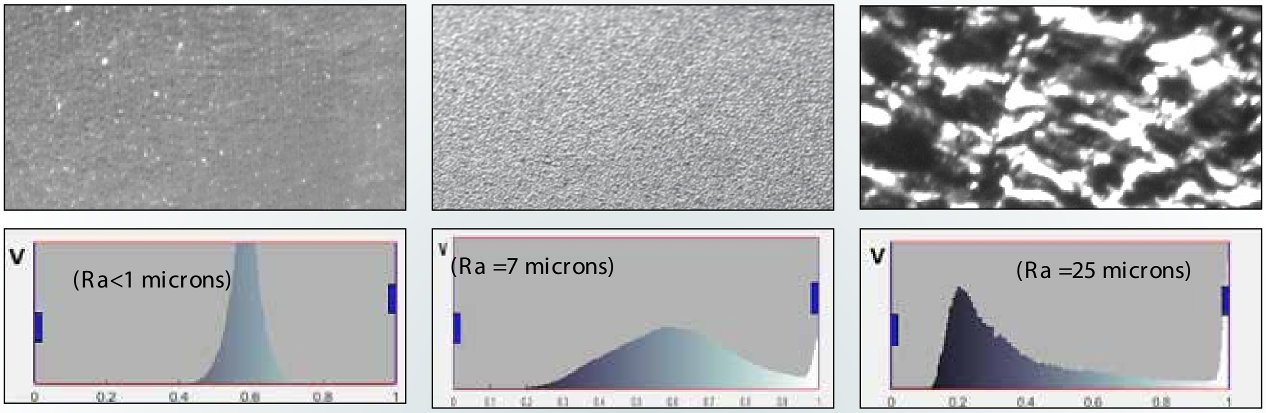

Figure 2. Characterization of surfaces with different roughness using high resolution camera with lighting strategy.

for feedback control. The NDI system includes an infrared thermal imager, a high-resolution visible camera, and a laser-induced breakdown spectroscopy (LIBS) to monitor, in real time, the melt pool temperature, thermal distribution, and alloy composition involved in melting and surface roughness/emissivity. The system also characterizes surface/subsurface defects (~10 micron precision), feeding its analysis back to the AM and SM machine for process optimization.

A breakthrough was made in the real-time calibration of surface emissivity to obtain the true temperature distribution of the processed layer (a patent has been filed, Jian Liu, "Method and Apparatus for Real Time, In Situ Sensing and Characterization of Roughness, Composition, Defects, and Temperature in Three-Dimensional Manufacturing Systems," Application number 16378485, 2019.). Figure 2 and Figure 3 reveal the correlation between surface roughness and the ratio of brightness/darkness at various grey level thresholds of the visible high-resolution camera. The correlation shows that by setting the threshold level at about 0.3, a linear relation between roughness and the ratio of brightness/darkness is achieved. This gives a foundation for the thermal camera to calibrate its emissivity map to extract the true thermal distribution map for printing parts and characterize their defects (Figure 3 right). Figure 4 compares true thermal distribution maps with and without defects for SS316L. This simple and practical approach provides an excellent foundation for further correlation between surface roughness and thermal distribution under residual stress and fatigue in the next level of research and development.

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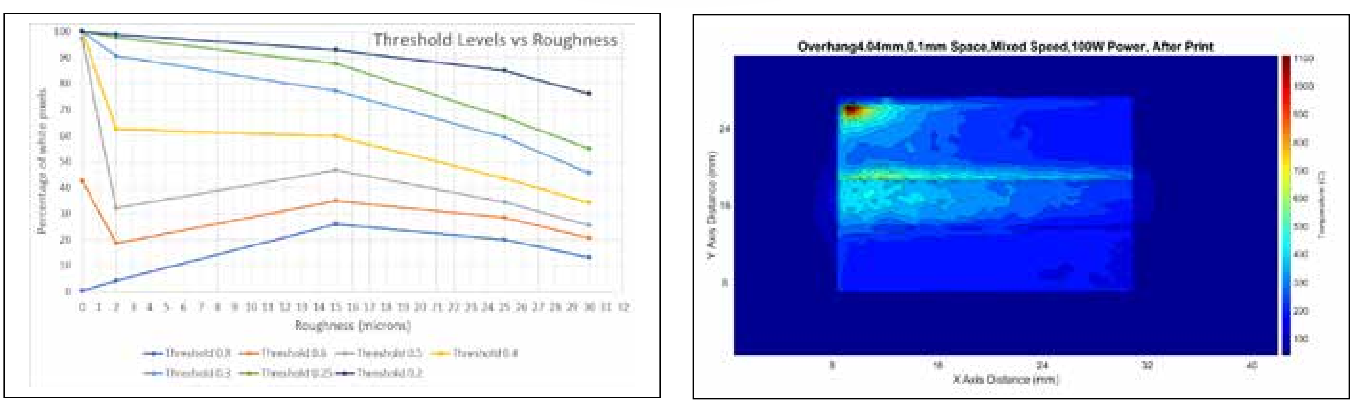

Figure 3. (Left) Percentage of bright pixels as a function of roughness under various types of gray level thresholds. (Right) True temperature extraction after emissivity correction with accurate surface roughness measurement. It clearly shows the true temperature distribution, boundaries of various sections, and defects.

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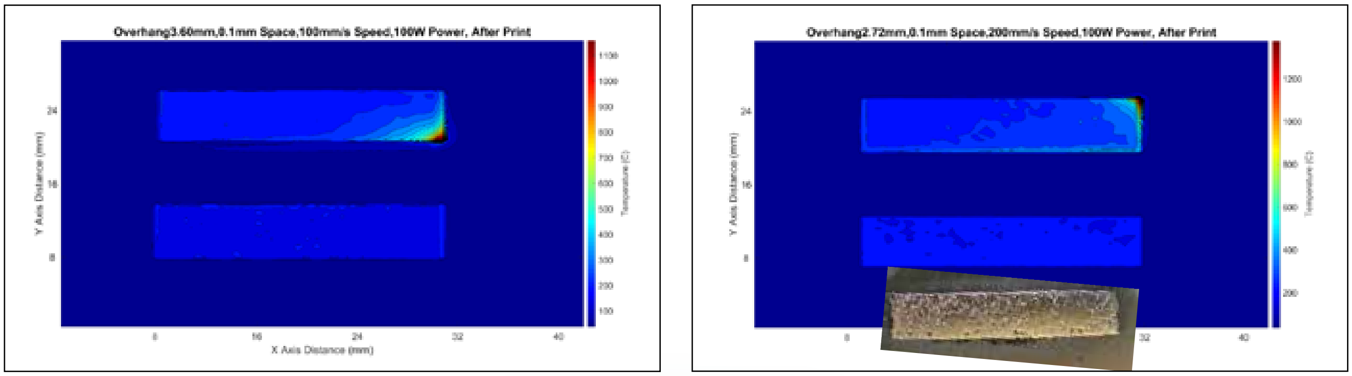


Figure 4. Thermal distribution after emissivity was calibrated with roughness for two cases: (left) good result was obtained for 100 W 100 mm/s; (Right) 100W 200 mm/s. Non-uniform thermal distribution was observed in thermal distribution map (TI), and associated defects were also reflected in the cut sample.

A feedback and control algorithm has been developed in PolarOnyx to evaluate and control the quality of printing parts in real time. Process parameters, such as laser power, temporal format, and scanning pattern, are integrated in the system. Figure 5 shows the difference between the controlled process and the uncontrolled processes for printing a 25 × 25 × 25 mm SS316L overhang. With this feedback control process, the overhang can be built with high density (99%) and less defects, compared to its other counterparts without feedback.

This demonstration builds the necessary foundation for our next step in developing fully intelligent AM system. We are working on integrating machine learning and artificially intelligent technology into the system to create multi-material complex structures with nuclear quality

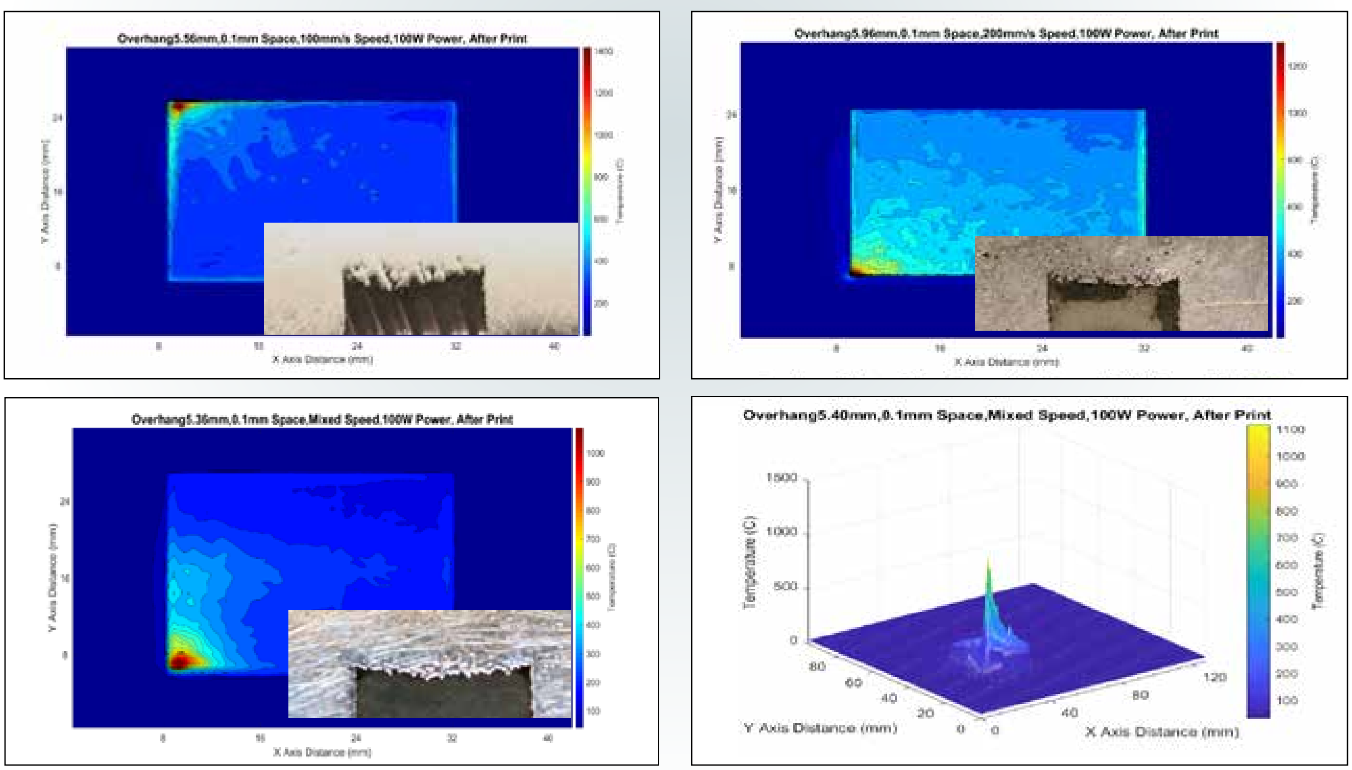
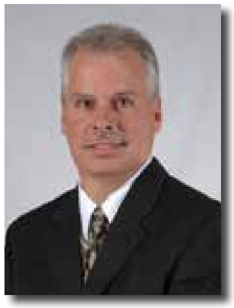
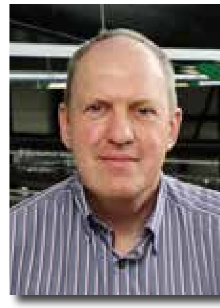


Figure 5. True thermal distribution map for three cases by using roughness measured from high-resolution visible camera to calibrate emissivity of thermal imager. Controlled process (bottom) shows better quality of overhang making, compared with (top left) 100 W and 100 mm/s; and (top right) 100 W and 200 mm/s.

Establishing Modular In-Chamber Electron Beam Welding Capability in the USA





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In 2017, the United States Department of Energy (DOE) launched a project with Electric Power Research Institute (EPRI), Nuclear Advanced Manufacturing Research Centre (AMRC) (UK), and NuScale Power (DE-NE0008629) to manufacture and assemble several critical sections of a 2/3-scale reactor pressure vessel (RPV) using various advanced manufacturing and fabrication technologies, including electron beam welding (EBW), diode laser cladding, powder metallurgy-hot isostatic pressing (PM-HIP), and advanced machining. Within this joint U.S./UK initiative, EPRI has taken the lead in the area of -powder metallurgy-hot isostatic pressing (PM-HIP) development, while Nuclear AMRC leads the electron beam welding (EBW) development. Combined, these technologies have the potential to significantly reduce fabrication and lead time, improve overall quality, and reduce manufacturing costs of next-generation power plants.

All EBW development/demonstration in the current project is being performed in a large electron beam (EB) vacuum welding chamber in the UK. No similar capabilities for large-scale EBW of thick-section components exists in the U.S. For the U.S. to fully implement EBW of large-scale components (small modular reactor [SMR] reactor pressure vessel [RPV] or containment vessel [CV]) at a major fabricator, an even larger (~35-ft long) vacuum chamber would be required using today's EBW technology. This has led EPRI to propose an alternative approach—modular i n-chamber (MIC) electron beam welding (EBW)—that could be readily implemented by U.S. industry at much lower cost.

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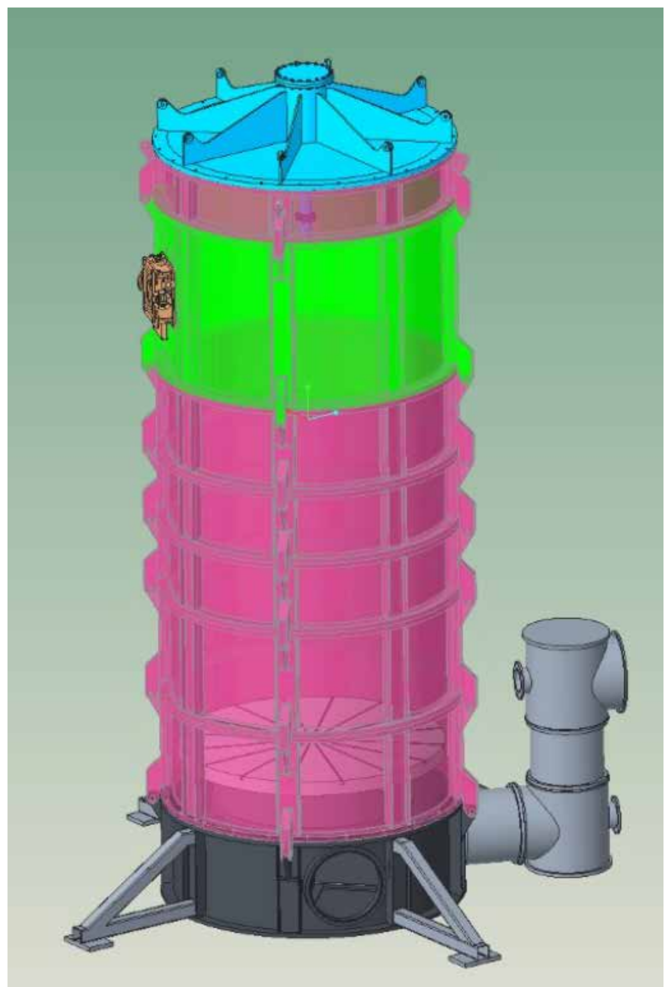

Figure 1. MIC-EBW system is shown in a fully stacked condition. It includes multiple spacer modules (in magenta) added above the manipulation stage (gray) and the EB gun and slide stage (green) positioned to complete an RPV girth weld at a higher location.

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Tasks

The modular in-chamber (MIC)-EBW capability is being developed under a separate DOE project (DE-NE0008846) consisting of two major phases:

1. Phase 1. EBW Equipment Design and Production
2. Phase 2. Full-Scale Modular In-Chamber Welding Demonstration.

Phase 1 of the project is be cost-shared with EPRI and NuScale Power and consists of four tasks. Task 1 focuses on detailed process planning for major elements of the MIC-EBW system/approach, including welding, inspection, and manufacturing. Tasks 2 and 3 look to design and fabricate two of the key elements of the EBW system:

- A vacuum pumping system capability, which will be used during SMR component assembly.
- An electron beam gun and slide, which will be used to complete each of the nine major girth welds in the NuScale Power SMR RPV design.

Task 4 is focused on the design of vacuum seals used to create a vacuum-tight seal between modular sections of the MIC-EBW system, and a demonstration of the MIC-EBW technology on small-diameter steel rings.

Current Status

The MIC-EBW approach will allow a manufacturer/fabricator to stack or de-stack individual modules to meet the given height of any major girth weld for the NuScale RPV. This approach allows the fabricator to increase the height of the vacuum system as the overall height of the RPV increases and is simply accomplished by adding individual spacer modules (Figure 1).

Several key items have been completed or are near completion in Phase 1 of the project. A draft of the key process planning elements (welding, inspection, and manufacturing) has been completed and is currently in review. This document describes all key process elements necessary for a fabricator to effectively perform fabrication of the NuScale reactor using the MIC-EBW system. Second, the design has been completed for the entire MIC-EBW system and drawings have been locked down. Detailed drawings have been generated for each of the major components: (1) base system, (2) vacuum/manipulation module and vacuum equipment, (3) EB module and EB welding equipment, (4) spacer module, and (5) a lid (cover) for the demonstrator system (key elements are shown in Figure 2). All major vacuum and EB equipment have been ordered and are being assembled. Lastly, a vacuum sealing design to be used between individual modules has been produced and will be evaluated over the next couple of months at the AMRC in the UK.

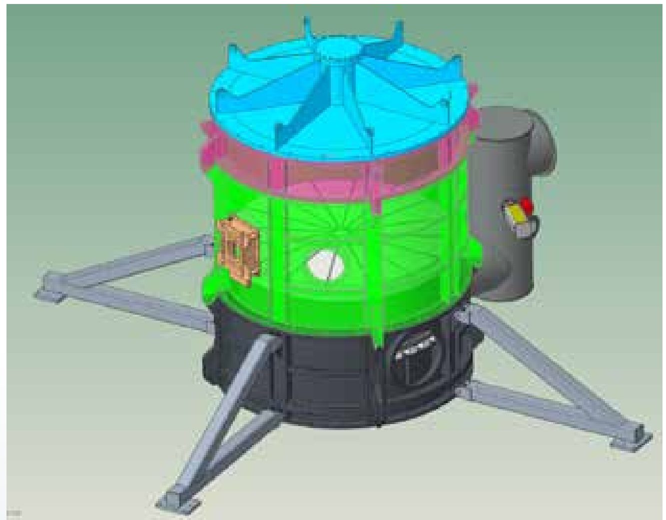

Figure 2. MIC-EBW Demonstrator will be used to demonstrate the approach on thick 10-ft-diameter rings produced from RPV steel.

Completion of Phase 1 of the project is expected in September 2020 at which point all major equipment, minus the module fabrication and full-scale demonstration, will have been completed. A medium-scale demonstration of the EBW and vacuum equipment is planned at PTR Precision Products in August 2020. This will be conducted on thick, 4-ft-diameter ring sections produced from reactor pressure vessel material. Once completed, the technology will be ready to move to Phase 2 of the project wherein large-scale (10-ft diameter) demonstrations will be performed at a major fabricator.

Impact, Value, Implications

The project will significantly advance EBW technology for large component applications and most importantly establish large-scale EBW capabilities for pressure-retaining components in the U.Ss. The technology is important to the U.S. because actual welding time for large-diameter (10 ft [3.05 m]) vessel girth welds can be reduced from weeks to less than 90 min. This represent a game-changing fabrication technology for the U.S.

Anticipated outcomes of the project include the following:

- Establish EBW capabilities for large, thick-section components (e.g., reactor vessels, steam generators, pressurizers, and wind turbines) in the U.S.
- Work directly with a U.S. fabricator/manufacturer to install, demonstrate, and commercialize capabilities for production.

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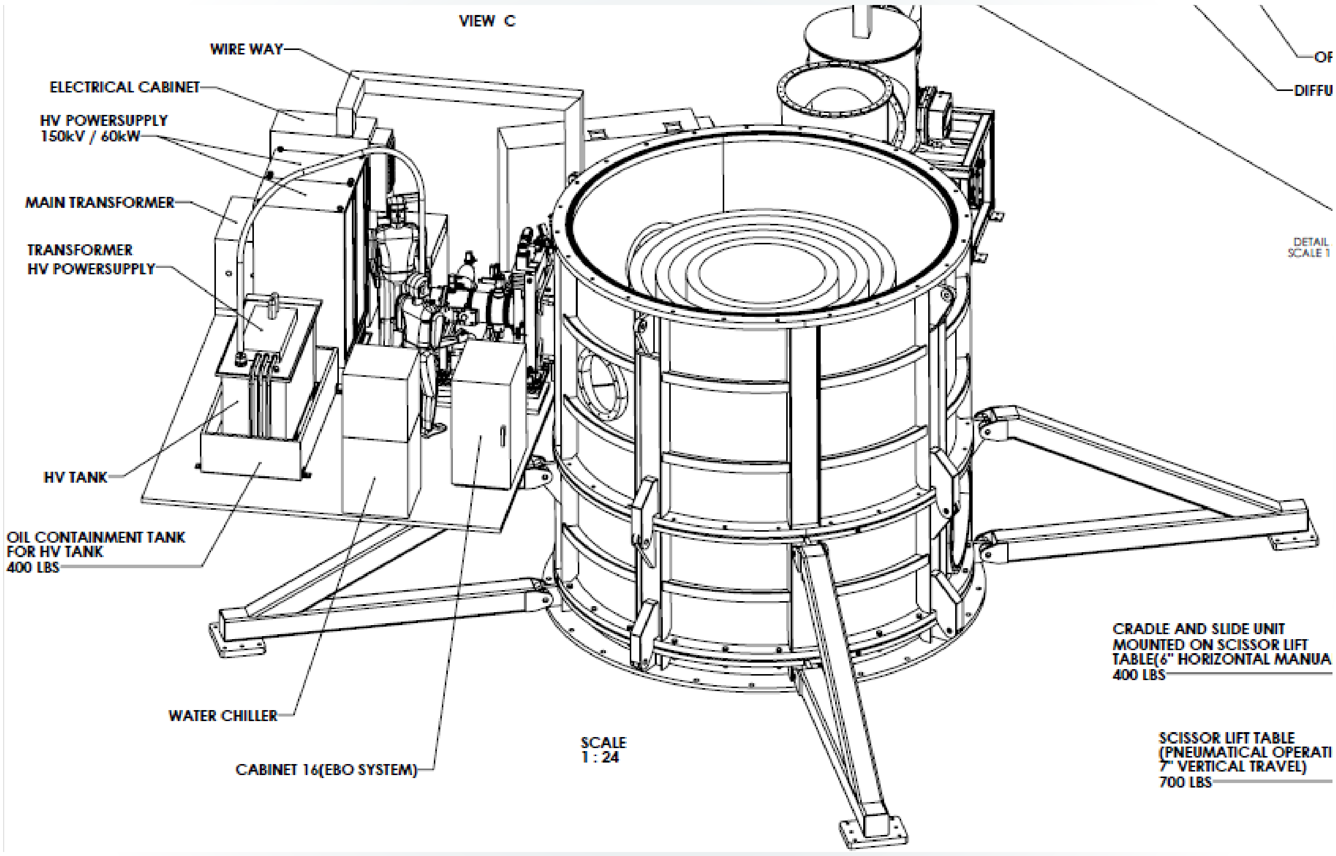

Figure 3. A conceptual drawing of the entire MIC-EBW system, including all modules, a platform for welding, and welding equipment.

- Successfully demonstrate that a large-diameter 10-ft (3.05 m)-thick section weld can be completed in less than 90 min of welding time.
- Establish modular EBW capabilities/approach that can be used across different component diameters. The EBW gun and slide can be detached and reattached to accommodate modules of different sizes.

Lastly, the technology has potential application in other industries including oil and gas, wind energy, and ship building.

Acknowledgements

Additional key members of the team include: (1) NuScale Power: Steve Wolbert and Derick Botha; (2) PTR Precision Products: John Dowd, David Trembley, Wilfried Klein, Ed Bonewitz, William Howe, and Derek Mayes; and (3) Advanced Manufacturing Research Centre(UK): Billy Redpath, James Coupe, Merv Alford, and Garth Nicholson.

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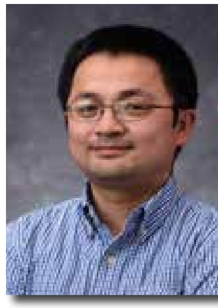
Optimized Dissolvable Supports for Laser Powder Bed Fusion Additive Manufacturing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Laser powder-bed fusion (LPBF) additive manufacturing (AM) has the ability to manufacture parts with complex geometries while significantly shortening lead times, improving performance and reliability through part consolidation, and broadening design freedoms. As the mechanical properties of LFBF metal parts improved, numerous industries began to take advantage of AM to either improve their designs or replace cast parts. For example, the nuclear industry is exploring AM to replace aging components as either drop-in replacements or new, improved designs. However, several challenges must be addressed before the nuclear industry can fully adopt the technology; specifically, 1) current post-processing techniques cannot remove the interior-support structures often found in parts not optimized for AM (e.g., replacement components), 2) post-processing is extremely expensive and can add weeks or even months to the processing time, and 3) support design is still an art that must balance minimized support volume against reduction in residual stresses that often lead to print failure.

This project aims to address these issues by developing an innovative approach to reduce drastically development and post-processing costs associated with LPBF manufacturing of complex nuclear components.
The approach will integrate self-terminating etching technologies for support dissolution, fast process simulation, and topology optimization to achieve these goals. The project objectives include

1. Development and validation recipes to dissolve support structures and reduce surface roughness using a self-terminating dissolution process for SS 316L and 17-4PH steels
2. Development of an automated support-structure design tool capable of maximizing the support dissolution rate and minimizing residual stress and distortion of LPBF parts
3. Design of LPBF processing with heat-treatment to optimize hierarchical-structure LPBF parts made of SS 316L, 17-4PH and Stellite 6 alloys by applying the integrated computational materials engineering (ICME) process structure-property modeling

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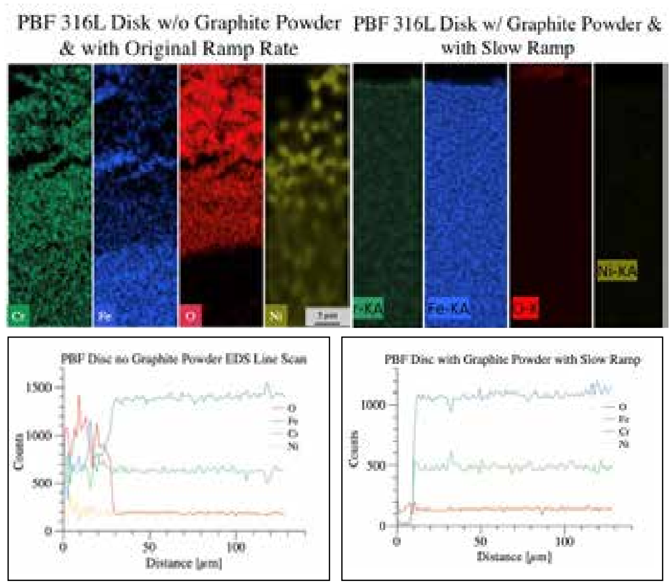

Figure 1. EDS micrographs of LPBF-processed 316L stainless steel under varying environmental conditions. These studies established that the atmosphere must be free of O2 and H2O, which can be achieved by adjusting the purging process and slowing the temperature ramp rate to give the sodium hexaferrocynate time to fully dehydrate.

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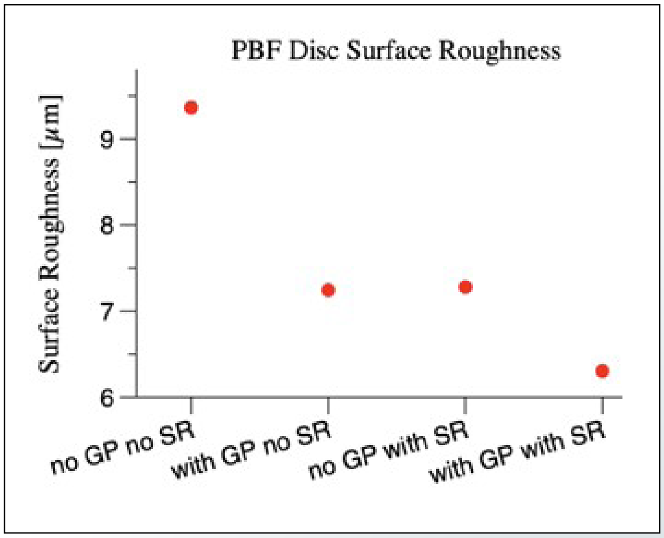

Figure 2. Surface roughness data after etching for various sensitization treatments. GP = graphite powder, SR = slow ramp rate. Notice that the post-etch Ra roughness drops to 6.2 µm by optimization of the sensitization process.

4. Design of surface heat-treatment recipes for enhanced mechanical properties

5. Demonstration of integrated technology that is capable of removing internal support structures, not assessable by post-machining, for two complex nuclear-reactor components in less than 24 hours.

Current Status

The outcome of this project objective is a validated recipe to sensitize and etch SS 316L components fabricated using LPBF. The energy-dispersive x-ray spectroscopy (EDS) in Figure 1 shows some of the sensitization optimization tests conducted. The initial recipe was tested in an open-atmosphere furnace with the part lightly coated in sodium hexaferrocyanate. To further reduce the O2 concentration at the component surface, the part was surrounded with graphite powder and then tested at different temperature schedules. Eventually, a process that fully sensitized parts without forming an oxide layer (which inhibits uniform etching) and without chromium migration was developed. As shown in Figure 2, optimizing the sensitization process reduced the Ra roughness by 30%, from 9.4 to 6.2 µm.

Using the recipe developed, a set-of-parameters study was conducted to find a wall thickness that could be dissolved (Figure 3). The test varied hatch spacing and the number of laser scans. The results of this study showed that the maximum thickness in the support structure is about 350 µm for complete dissolution.

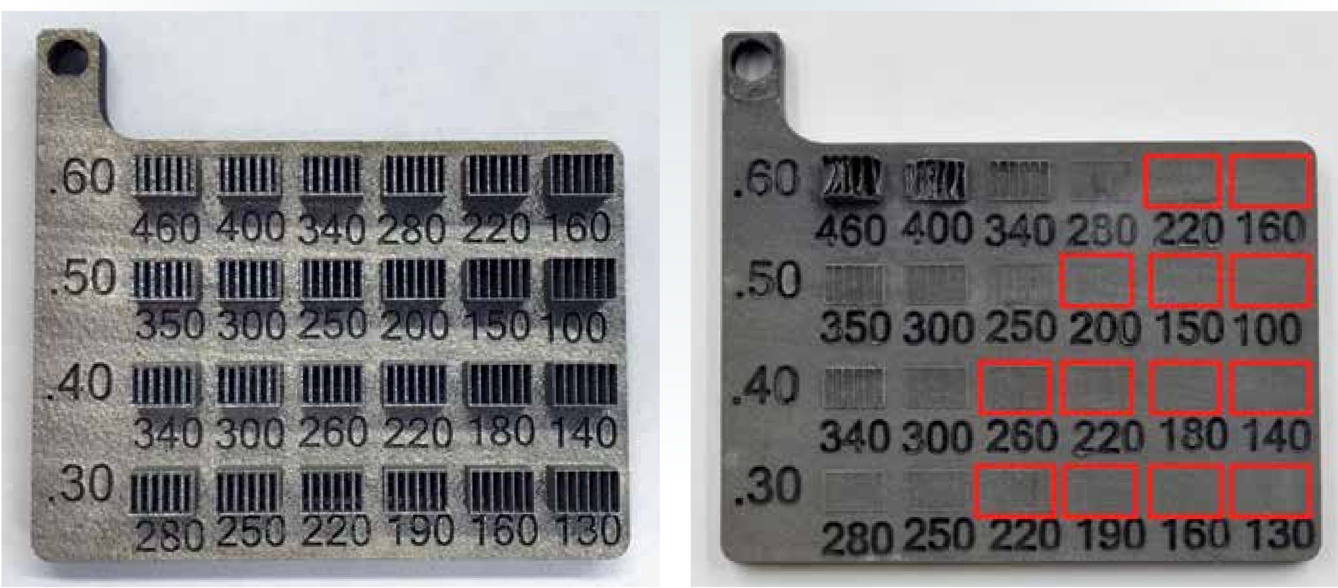

Figure 3. Printed 316L samples with different wall thicknesses tested for dissolvability (a) before and (b) after dissolvability testing.

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