AMM Newsletter
Advanced Methods for Manufacturing
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## Advanced Methods for Manufacturing Update

Tansel Selekler has been named Program Manager for the U.S. Department of Energy Office of Nuclear Energy's (DOE-NE) Advanced Methods for Manufacturing (AMM) program. She is also the program manager for the Nuclear Science User Facilities (NSUF) program. She succeeds Alison Hahn who has joined the Light Water Reactor Sustainability (LWRS) program. Alison has been the program manager for AMM since its inception in 2011.

**Tansel Selekler**
Program Manager, DOE-NE AMM

Tansel comes to the program with 20 years of experience in government and industry. She holds a degree in nuclear engineering (major) and in mechanical engineering (minor) from the University of Maryland. She also received an MBA degree from Maryland. Tansel managed the Energy Innovation Hub for Modeling and Simulation program before assuming responsibility for the NSUF and AMM programs. In her 13 years in NE, she has worked for the Nuclear Power 2010 program, Transient Reactor Test Facility (TREAT) restart, nuclear facilities management, and Nuclear Energy Advanced Modeling and Simulation programs. Prior to DOE, Tansel spent seven years as a nuclear engineer at Bechtel Power Corp. Tansel reports to Tom Miller, Director, Office of Accelerated Innovation in Nuclear Energy. Tansel's e-mail address is Tansel.Selekler@nuclear.energy.gov

DOE-NE received 37 applications for funding as part of the FY2018 Consolidated Innovative Nuclear Research (CINR) AMM program. The proposals currently are undergoing Relevancy Reviews, and award selection is anticipated in June.

In FY 2018, NE established a separate Funding Opportunity Announcement (FOA) for the U.S. nuclear industry. The FOA is designed to support innovation and competitiveness by directly sharing costs on cross-cutting applied research and development activities. Additional information is available at: https://www.id.energy.gov/NEWS/FOA/FOAOpportunities/FOA.htm

On November 28 and 29, 2017, the NRC held a meeting to discuss Additive Manufacturing (AM) for Reactor Materials & Components. The NRC's objectives for the meeting were to engage with industry and government counterparts to obtain information needed for anticipated licensing actions related to AM, and to come up to speed on the key related issues. Copies of the presentations from the meeting are available in the NRC's Agency-wide Documents Access and Management System (ADAMS, https://www. nrc.gov/docs/ML1733/ML17338A880.html ).

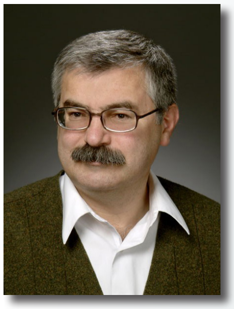
## In This Issue





U.S. DEPARTMENT OF ENERGY

# Environmental Cracking and Irradiation Resistant Stainless Steel by Additive Manufacturing





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Metal additive manufacturing (AM), or 3D metal printing, is an advanced manufacturing method that can create near net shape structures directly from a computer model. The process utilizes a high-power laser to precisely melt and solidify alloy powder layer-by-layer and creates a final geometry directly from its 3D computer model. This technology can provide the capability to rapidly fabricate complex parts that may be required to enhance the integrity of nuclear reactor internal components. Such opportunities of rapid turnaround may be observed during plant refueling outages, and AM parts can be rapidly custom designed and deployed within the short outage interval. AM of 316L stainless steel components can add business benefits of fast delivery on repairing hardware, installation tooling, new design prototype tests. In the meantime, the improved material properties will also reduce the overall component cost, plant asset management cost, and increase the plant reliability by an improvement in materials performance.

### *Current challenges*

While many nuclear AM projects are currently on-going, to be able to fully push the AM technology toward commercialization there are three technical gaps that still limit its wide adoption at General Electric (GE) and in the entire nuclear industry. (1) The lack of complete knowledge of AM materials, because the commercial nuclear power industry requires specific properties and data making it difficult to acquire regulatory approval, develop nuclear specifications, and finalize commercialization. The materials properties required include resistance to stress corrosion cracking (SCC), resistance to irradiation assisted stress corrosion (IASCC), and resistance to swelling. (2) AM's current intrinsic high manufacturing cost (compared to well-known conventional manufacturing) limits its use in nuclear applications. Utilities have indicated they are willing to pay the extra cost for AM if the value offered is higher than that of conventionally manufactured components. (3) There is no pre-existing business practice in AM in the nuclear industry, which includes lack of knowledge in component design, fabrication, and qualification, specific nuclear material specifications, the path for regulatory approval, production process, cost model, and business case analysis.

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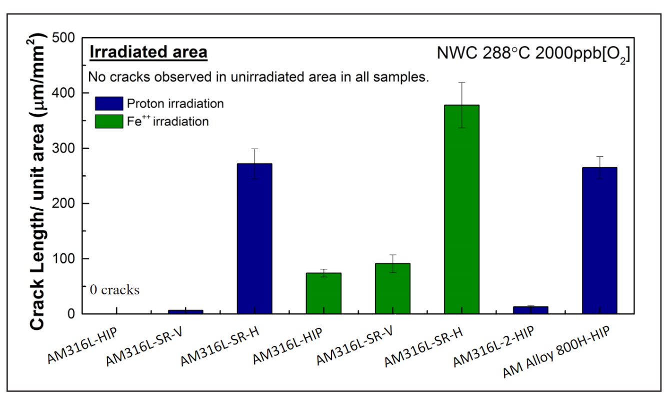


***Figure 2. Bonded 304 SS and A516 PVS interface after FSAM***

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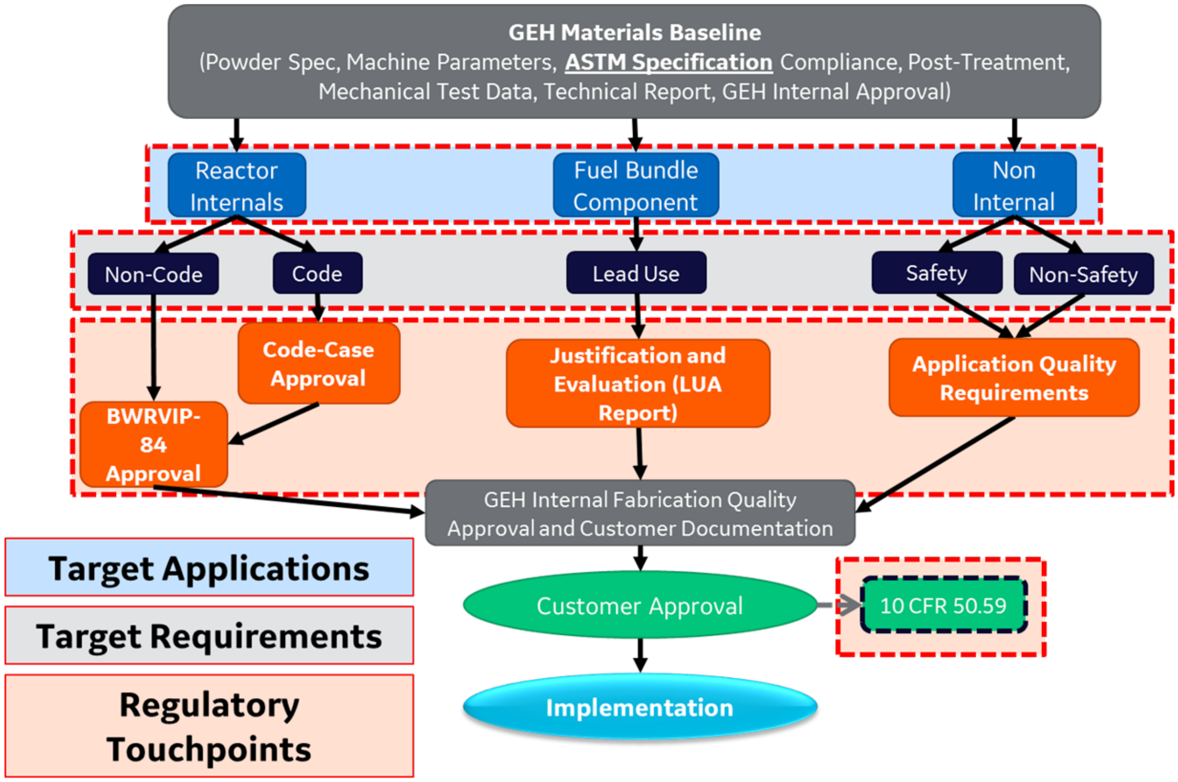


***Figure 4. Mandrel bend test with different elongation at the FSAM interface***

### *Research accomplishments*

To close the technical gaps and further push the AM technology into GE product lines, the current research program was designed to tackle these three issues through two parallel approaches. On one hand, the team members at GE Global Research, Auburn University, University of Michigan, and Oak Ridge National Laboratory focused on fundamental material research and AM process/material optimization to support the nuclear specification via AM stainless steel development. These efforts included: (1) understanding correlations between manufacturing process, heat treatment, microstructure, and specific nuclear material properties; (2) evaluating mechanical properties of AM stainless steels under different heat treatment conditions and temperatures; (3) comprehensively understanding SCC, corrosion fatigue, IASCC, and irradiation resistance properties of AM stainless steels, including effects of microstructure, heat treatment, stress intensity factor value, amount of cold work, crack orientation, oxidizing vs. reducing conditions, and porosity; (4) developing new AM stainless steels with improved SCC resistance; (5) recommending elimination of hot isostatic pressing to reduce manufacturing cost.

Figure 1 shows the comparison of IASCC susceptibility among different AM 316L SS and AM Alloy 800H specimens.

At the same time, extensive work has been done in parallel at GE Hitachi Nuclear Energy to develop nuclear product regulatory approval and commercialization strategies. Figure 2 shows an illustration of the process for nuclear application and regulatory approval. For reactor internal components, the BWRVIP-84 rules and ASME Code Case paths have additional data requirements specific to nuclear reactor applications.

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Results from the two-year material research were consolidated to form a baseline for GE Hitachi Nuclear internal AM materials specifications. The AM design and fabrication process was executed with a rigorous nuclear quality assurance (QA) oversight program to produce three nuclear fuel debris filters (Figure 3). These parts were subjected to materials testing and evaluation and results showed that the AM produced filter components have the pedigree to be considered for in-reactor use. The GE Nuclear component inspection and qualification program was adapted and executed for the first time on AM parts (Figure 4). This included supplementing the standard GE Nuclear inspection processes with CT and Blue Light scanning to better characterize AM tolerances. The cost per part and capital investment requirements for a production scale facility were determined via a mathematical model developed in collaboration with the GE Greenville AMW. As part of the commercialization analysis, a customer with serious interest in using these AM produced nuclear debris filters in a power reactor was identified.


***Figure 3. GEH Boiling Water Reactor fuel bundle with debris filter insert.***

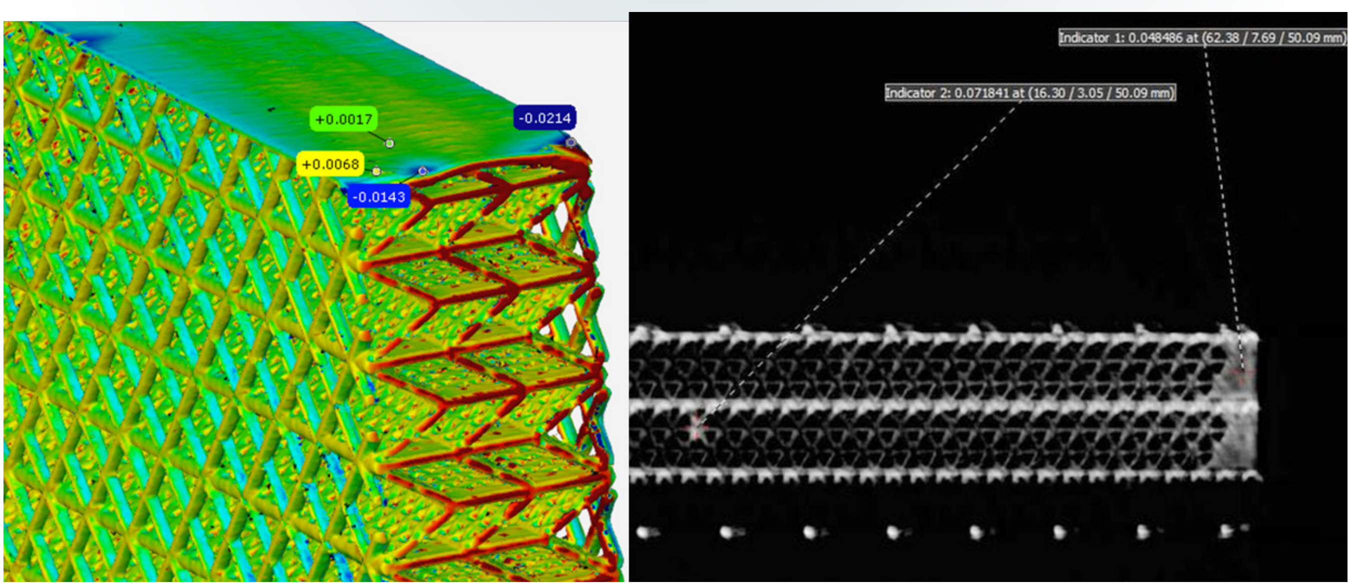


***Figure 4. CT Scan of Debris Filter Design Interior (red means it is outside allowable tolerances).***

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

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The Fukushima nuclear accident of 2011 has highlighted the importance of designing safety-related nuclear facilities for accident thermal scenarios combined with design basis and beyond design basis shaking. While the probability of both events occurring simultaneously is low, the Fukushima event demonstrated that severe environmental conditions may trigger accident thermal loading, and that subsequent aftershocks, potentially as intense as the main shock, may occur during the accident thermal event.

Current U.S. standards for reinforced concrete (RC) or steel-plate composite (SC) walls in safety-related nuclear facilities provide little procedural guidance for considering the effect of accident thermal loading on the seismic performance of walls. The effect of accident thermal loading on the seismic performance of SC or RC walls has not been investigated experimentally or numerically. Prior research focused on either seismic behavior or accident thermal loading but not both in combination.

The combination of accident thermal loading and Safe Shutdown Earthquake (SSE) will present a significant design challenge for buried SMRs because postulated accident scenarios will cause higher elevated temperatures for longer durations in their small and/or constrained spaces. For approval, the regulator will require extensive technical information and clear evidence of safety for the accident thermal and SSE loading combination, which may compromise the licensing schedule.

This research focuses on the effects of accident thermal conditions on the seismic performance of SC walls and RC walls. For SC walls, the steel faceplates (with no protection) are directly exposed to elevated temperatures resulting from accident thermal conditions. The differential temperatures between the steel faceplates and concrete infill, and the nonlinear thermal gradients, lead to concrete cracking and potential overstressing of the steel faceplates (primary reinforcement) particularly during seismic events. For RC walls, the nonlinear temperature gradient through the thickness of the concrete section will lead to concrete cracking and significant stress in the steel rebar in the absence of earthquake shaking.

The project involves experimentally investigating the seismic (in-plane shear) performance of structural walls subjected to accident thermal loading. Following the experimental program, numerical models were developed and benchmarked for predicting the seismic performance of structural walls subjected to accident thermal loading and design basis and beyond design basis earthquake shaking. The benchmarked models were used to conduct

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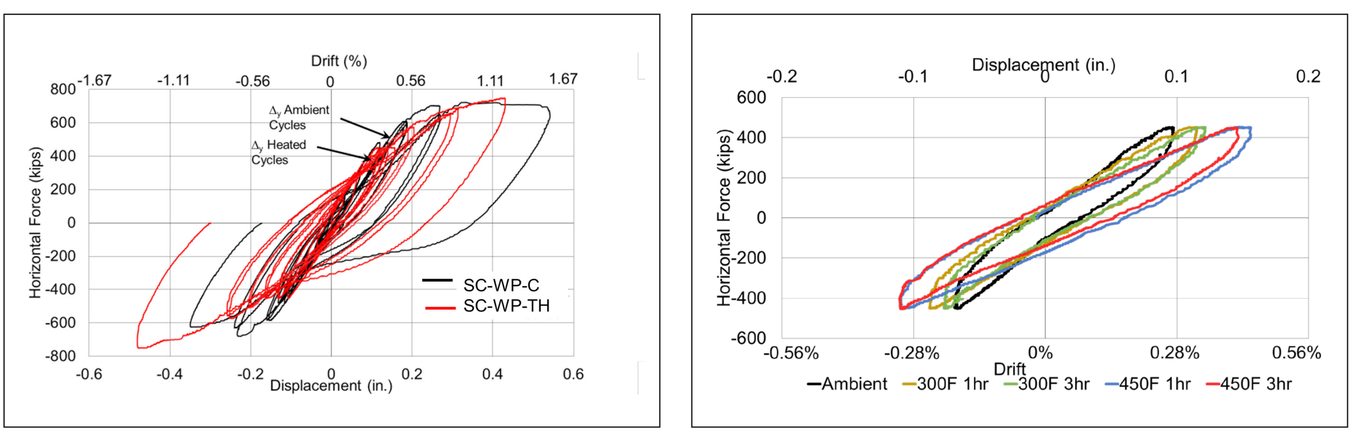


***Figure 1. Response of SC Wall pier specimens***

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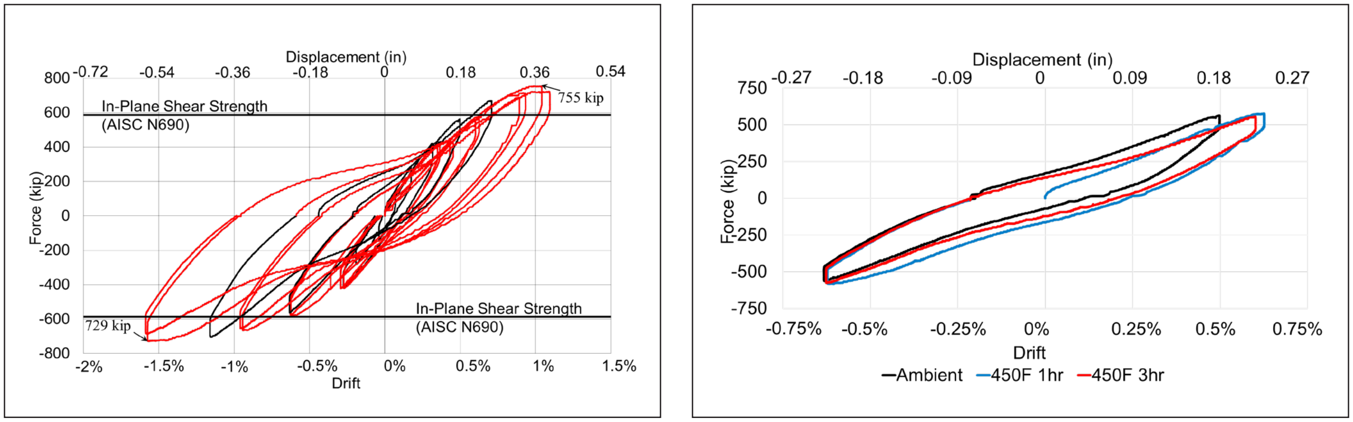


***Figure 2. Response SC wall specimen***

analytical parametric studies to evaluate the effects of a wide range of material, geometric, structural detailing, thermal loading, and seismic loading parameters, including those from experimental program.

### *Current Status*

The experimental investigations have been conducted, and benchmarked finite element models have been developed. The experimental observations and conclusions are summarized here.

The SC wall tests comprised of three specimens. Two identical SC wall pier (without boundary elements) specimens were tested. One specimen (Control, SC-WP-C) was subjected to just cyclic in-plane loading. The second specimen (SC-WP-H) was subjected to combined seismic and thermal loading. One SC wall specimen (with boundary elements, SC-W-H) was subjected to combined seismic and thermal loading. Four RC wall specimens were tested. Two specimens each had a reinforcement ratio of 1% (RC-1-SSH-300 and RC-1-SSH) and 2% (RC-2-TH and RC-2-SSH). The heated specimens were subjected to two magnitudes of temperatures (300˚F and 450˚F) and two durations of heating (one hour and three hours for SC specimens). Two heating protocols were employed for RC specimens; steady-state heating (SSH), where the specimen is subjected to continued heating while in-plane cycles are applied, or Transient Heating (TH) where the specimen is subjected to cyclic thermal and in-plane loading.

Figure 1a presents the comparison of force-displacement response for SC-WP specimens. Typical accident temperatures do not significantly reduce the strength

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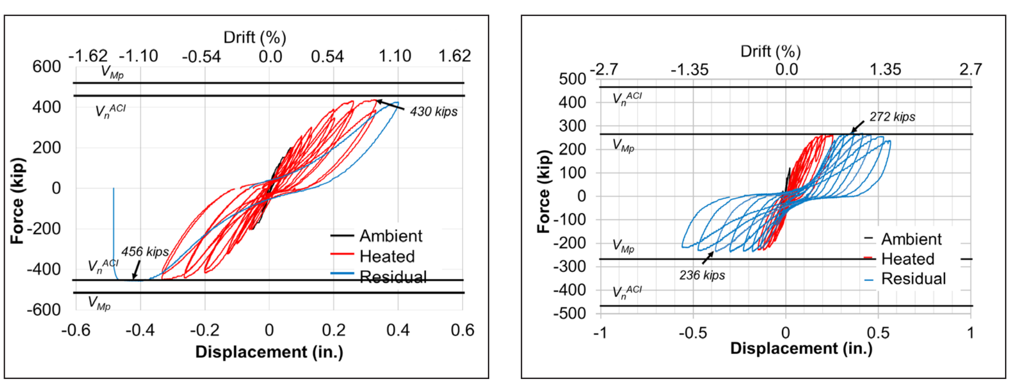


***Figure 3. Force displacement response of RC specimens***

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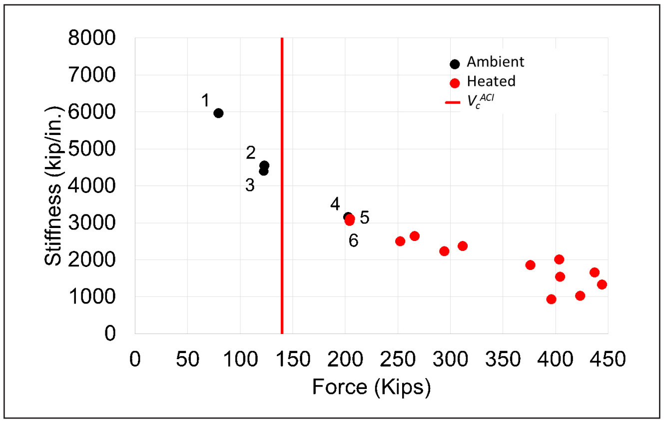


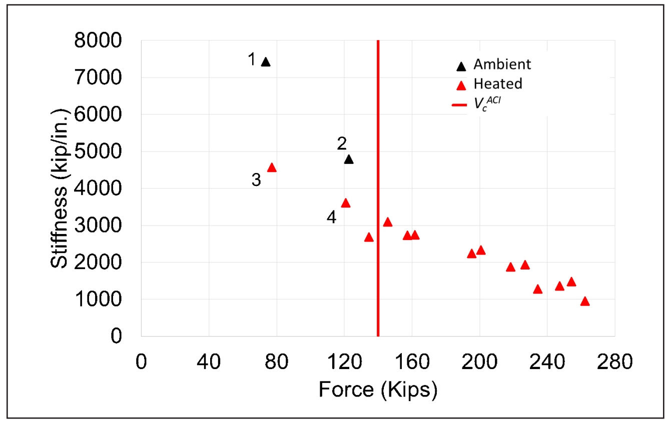


***Figure 4. Stiffness degradation for RC specimens***

of SC wall pier specimens. However, there is a significant reduction in stiffness of the heated specimen (apparent from Figure 1b, which shows the reduction in stiffness for 0.75Fn heated cycles in comparison to ambient cycle). A similar trend was observed for SC wall specimen (Figure 2). SC-W-H specimen reached a peak strength about 30% higher than nominal strength (using measured properties) per AISC N690s1. As seen in Figures 2a and 2b, the heated stiffness of the specimen was significantly lower than the ambient stiffness.

The strength response of heated RC specimens was consistent with that of SC specimens. Figure 3a shows the force-displacement response of RC-2-TH, with the measured strength with 5% of the nominal strength per ACI 349. Similarly for RC-1-SSH-300 (Figure 3b), the measured strength was approximately equal to its plastic moment capacity. The stiffness reduction in RC walls due to thermal loads depends on the extent of pre-existing flexural or shear cracking in the wall. As seen in Figure 4a (for RC-2-TH), thermal loads did not result in a significant reduction in stiffness because the specimen had already cracked in flexure and shear. However, for RC-1-SSH-330 (Figure 4b), the thermal loads do result in a reduction in stiffness as they cause additional shear cracking.

### *Conclusions*

Typical magnitude and durations of thermal loads do not significantly reduce the strength of wall structures. The strength for thermal load combinations can be determined using existing code provisions for ambient temperatures. However, the stiffness of wall structures is reduced considerably as thermal loads are applied. The reduction in stiffness is attributed to extensive concrete cracking due to non-linear thermal gradients through the thickness of the specimens. The extent of the reduction in the stiffness depends on the magnitude and duration of accident temperatures (higher stiffness reduction is observed for surface temperatures of 450°F in comparison to 300°F). For SC wall, the stiffness reduction is of the magnitude of about 40%. For RC walls, the extent of stiffness reduction is due to additional concrete cracking, and once the concrete is cracked in flexure or shear, thermal loads will not result in any additional cracking. The experimental observations will be verified using benchmarked finite element models. The observations can be employed for analysis and design of wall structures for combinations of thermal and seismic loads.

# Development of Nuclear Quality Components Using Metal Additive Manufacturing

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Multi-material parts enhance functionality and performance in a variety of applications in the nuclear power industry. A major challenge in manufacturing multi-material components is the joining of dissimilar metals. Traditional joining methods, including brazing, welding, and soldering, can result in the formation of precipitates, intermetallics, and distortions at the weld interface that are detrimental to the part's performance.

This multi-institutional collaborative project, comprised of RadiaBeam Systems (RadiaBeam), the University of Texas at El Paso W.M. Keck Center for 3D Innovation (UTEP-Keck), and the University of California at Berkeley (UCB), focused on the development of electron beam-based additive manufacturing (AM) process for joining austenitic steels to nickel-based superalloys for use in the nuclear power industry. Process parameters and technology to join Inconel 718 (INC718) and Inconel 690 (INC690) alloys to 316L stainless steel (SS316L) were developed using an Arcam S12 Electron Beam Melting (EBM®) AM platform, modified for high temperatures at UTEP-Keck.

EBM AM is a powder-bed fusion fabrication process that uses a focused electron beam to fully melt metal powder in a layer-by-layer fashion. The use of an electron beam makes the energy deposition process very efficient, fully melting a variety of metallic powders in an evacuated processing environment resulting in limited contamination of oxides and nitrides, and providing a high quality metallurgical joint while minimizing the thermal damage to surrounding material. Figure 1 is an overview of the process to achieve multi-material parts starting from a precursor powder material.

In Phase I of the project, basic feasibility was established by successfully joining Inconel 718 to SS316L. Characterization of the EBM INC718 on SS316L interface revealed minimal thermal effects (e.g. reduced presence of precipitates) and heat affected zone (HAZ) depths as small as 443±56µm. Results of the INC718-SS316L EBM fabrication have been published (A. Hinojos, et. al., Material & Design, Vol. 94, 15 March 2016, pages 17-27).

In Phase II of the project, EBM AM process parameters were developed for joining of INC690 to SS316L, and multi-material tensile bars and irradiation targets were fabricated using EBM AM and characterized. Measured mechanical properties of samples consisting of Inconel 718 and 690

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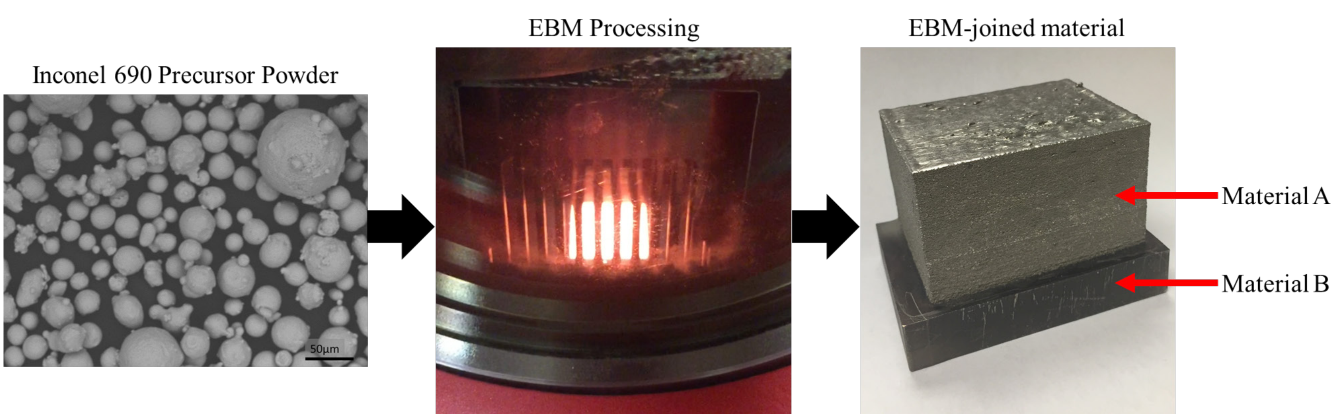


***Figure 1. Joining process for non-standard materials***

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| | EBM Inc718 Wrought SS | EBM Inc690 Wrought SS | EBM SS Wrought Inc718 | EBM SS Wrought SS | Wrought SS | Wrought Inc718 | EBM SS | EBM Inc690 |
|---|---|---|---|---|---|---|---|---|
| UTS (MPa) | 807±93 | 603 ±34 | 518±80.5 | 567.5±15 | 621±6 | 893±46 | 800±78 | 669±44 |
| YS (MPa) | 568±57 | 377±39 | 419±23.5 | 354±29 | 327±13 | 460±29 | 577±47 | 527±19 |
| Strain (mm/mm) | 0.27±0.05 | 0.24±0.008 | 0.10±0.04 | 0.28±0.09 | 0.53±0.01 | 0.39±0.02 | 0.37±0.03 | 0.22±0.02 |
| Elongation (%) | 27% | 24% | 10% | 28% | 53% | 39% | 37% | 22% |
| Young's Modulus (GPa) | 2.96±0.18 | 2.56±0.13 | 5.24±1.0 | 2.23±0.82 | 1.17±0.03 | 2.31±0.20 | 2.19±0.16 | 3.11±0.28 |

***Table 1: Measured mechanical properties for EBM deposited materials on various substrates***

joined to 316L Stainless Steel, as well as comparison with wrought material, are summarized in Table 1. The first nanoindentation data on as manufactured and ion beam EBM AM multi-materials were collected, and summarized in Figure 2.

Irradiation of the samples was performed at the Los Alamos National Laboratory (LANL) Ion Beam Materials Laboratory (IBML). Nanoindentation testing was carried out by UC Berkeley on ion beam irradiated EBM joints between Inconel and austenitic stainless steel. In summary it is observed that even the small doses of irradiation (~1 dpa) employed in this study result in significant hardening in both wrought and EBM alloys in a similar fashion. The EBM joint materials were shown to display a similar response to irradiation compared with the wrought material (See Figure 2). The only major outlier was the wrought Inconel that was subjected to EBM SS melting. This appears to be a consequence of the process itself of electron beam melting stainless steel atop this wrought sample, which causes the hardening to near-saturate prior to any irradiation. However, additional microstructural evaluation is necessary to determine the underlying microstructural changes resulting in the hardening.

Electron-beam based AM shows excellent promise for the efficient (cost-effective) production of multi-material parts for the nuclear power industry. The feasibility of joining INC718 and INC690 to SS316L has been established, and the EBM AM process has been shown to produce parts with improved joint qualities compared to traditional welding methods. RadiaBeam is currently in the process of developing a custom electron beam-based AM system. RadiaBeam's Large Electron beam-based Additive manufacturing Platform (LEAP) system has a build envelope of > 2000 mm x 800 mm x >900 mm (LxWxH), and will feature multi-material processing capability. The development of RadiaBeam's LEAP represents a path to realizing larger AM parts of interest to the nuclear power industry.

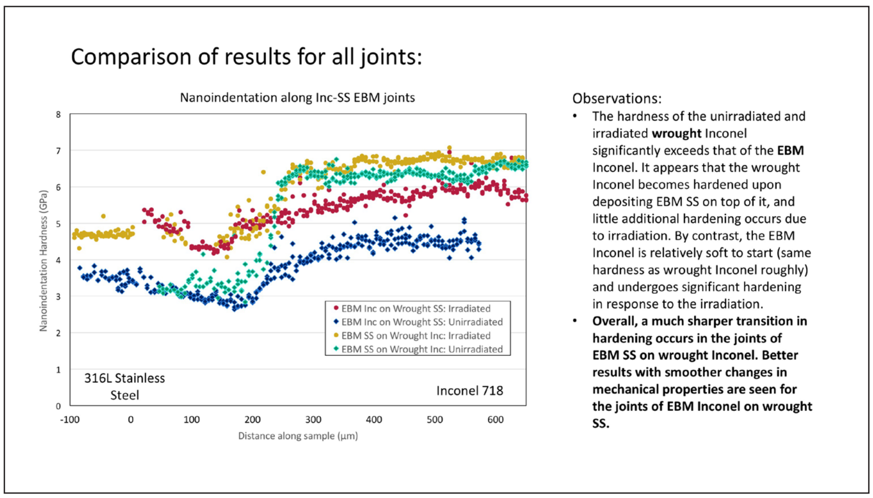


***Figure 2: Comparison of nanoindentation results in both joints for irradiated and nonirradiated samples.***

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