Additive Manufacturing Roadmap for the Nuclear Power Industry

Metal Alloy AM Technologies

ISSUE STATEMENT

Additive Manufacturing (AM) is a novel fabrication technology that has been the focus of significant and increasing research and development in recent years. The past decade has seen significant progress in the availability and adoption of metal alloy AM technology.

AM technologies, using both polymers and metal alloys, have been widely adopted in numerous industries outside of nuclear, in particular medical and dental devices, the automotive industry, and the aerospace industry. The nuclear industry is now seeing additively manufactured components used in nuclear power plants [2] and even within reactor cores [3, 4]. However, increased understanding of AM technologies is needed before the advantages can be fully realized. Widespread deployment of many advanced manufacturing methods such as AM is also complicated by lack of standards, ASME acceptance and regulatory approval.

DRIVERS

EPRI's Advanced Manufacturing Research Focus Area aims to identify, develop, qualify and implement more economical advanced manufacturing methods (AMM) that improve component performance and supply chain delivery. EPRI laid out various projects to implement these innovative techniques within the nuclear industry via its *Advanced Manufacturing Methods (AMM) Roadmap* [6]. A subset of the AMM Roadmap includes additive manufacturing as one of these high priority AMMs.

EPRI performed a comprehensive investigation focused on AM, developing this roadmap (and associated technical report 3002018276) for the implementation of additive manufacturing into the nuclear industry. As part of this work, the current state of the art in the development of AM technologies is reviewed, key gaps to the widespread adoption of AM within the nuclear power industry are identified, and a roadmap for addressing these gaps is presented.

Metal alloy AM is of interest to nuclear plant operators and equipment manufacturers for a number of reasons:

- Manufacture complex geometries that are not possible with traditional subtractive technologies or are more expensive.
- Manufacture in-kind replacements for obsolete parts via reverse engineering. This is particularly attractive for obsolete parts where the original manufacturer or tooling no longer exists.
- Increase reliability, reduce part count, and reduce manufacturing costs by integrating part assemblies into a single, more complex part.
- Bring new products to market faster, with faster design cycles and no need to develop custom tooling.
- Control part microstructures in certain regions or over the entirety of a part in order to achieve favorable properties in those regions.
- Embed sensors and other electronics within the fabrication of a structural part.
- Simplify inventory and supply chain management.
- The potential ability to join dissimilar materials using compositionally graded alloys.

RESULTS IMPLEMENTATION

EPRI, along with stakeholders in the nuclear power industry will use this roadmap to help align efforts to more efficiently address the key obstacles that the nuclear power industry must address to facilitate widespread adoption of metal alloy AM technologies. Research organizations and those who provide funding to these organizations can use this work to help prioritize essential projects. EPRI is supporting the closure of these key gaps within its Advanced Manufacturing Research Focus Area in order to make AM available to nuclear designers and fabricators. An example of this is the EPRI led U.S. Department of Energy project DE-NE0008521 which culminated in the submittal of an ASME Section III Data Package and Code Case for AM LPBF 316L [5].

RISKS

Risks associated with the implementation of this additive manufacturing roadmap within the nuclear industry, similar to various advanced manufacturing techniques, is tied to the acceptance of the technologies by Code or Regulatory authorities and the time that it takes to develop and demonstrate a new technology for nuclear use. These risks can be addressed by demonstrating the approaches in non-safety applications and obtaining valuable operating experience and prove-out.

ADDITIONAL INFORMATION

This roadmap is presented in more detail within EPRI Technical Report 3002018276 – "Additive Manufacturing Roadmap for the Nuclear Power Industry." Users can refer to this report for further details and descriptions on the gaps identified within this roadmapping effort and proposed solutions to close said gaps.

REFERENCES

1. *Advanced Nuclear Technology: Additive Manufacturing Roadmap for the Nuclear Power Industry—Metal Alloy AM Technologies*. EPRI, Palo Alto, CA: 2020. 3002018276.
2. "Printing Nuclear Parts," *Nuclear Engineering International*, Vol. 62, No. 755, pp. 26-28, 2017.
3. Cleary, W., and Karoutas, Z., "Fuelling Additive Manufacturing," Nuclear Engineering International, Vol. 62, No. 758, pp. 24-25, 2017.
4. "Framatome's breakthrough 3D-printed elements complete first cycle in a reactor," Framatome, Nov. 4. 2020, https://www.framatome.com/EN/businessnews-2014/framatome-s-breakthrough-3dprinted-elements-complete-first-cycle-in-areactor.html.
5. *ICME and In-Situ Process Monitoring for Rapid Qualification of Components Made by Laser-based Powder Bed Additive Manufacturing Processes for Nuclear Structural Applications*. EPRI, Palo Alto, CA: 2020. 3002018273.
6. EPRI Advanced Manufacturing Methods (AMM) Roadmap for the Nuclear Industry.

RECORD OF REVISION

This record of revision will provide a high level summary of the major changes in the document.

Revision	*Description of Change*
0	Original Issue: March 2021

EPRI RESOURCES

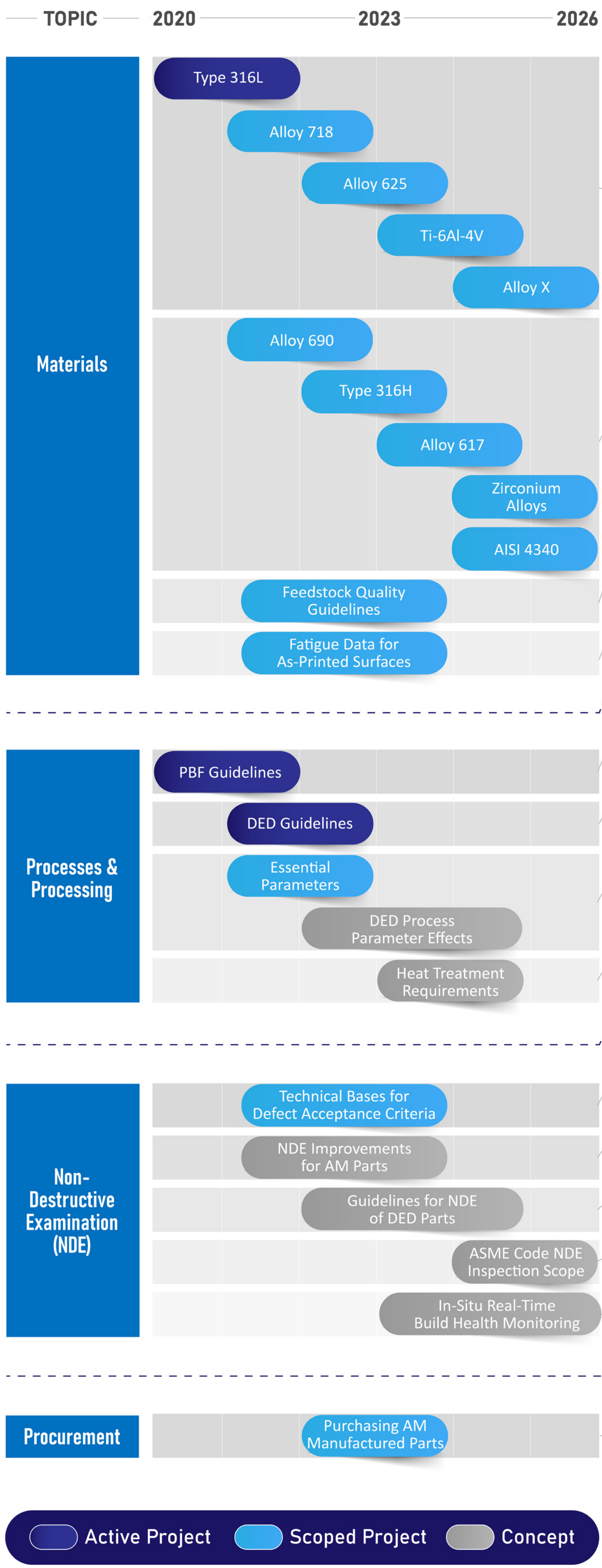
Marc Albert, Sr. Technical Leader
704.595.2187, malbert@epri.com

David Gandy, Sr. Technical Executive
704.595.2695, davgandy@epri.com

Stephen Tate, Technical Leader
980.495.7417, state@epri.com

Reach out to these resources for more information on EPRI's overarching AMM Roadmap

Additive Manufacturing Roadmap
for the Nuclear Power Industry



GAP	NEED	ACTIONS
AM Marketplace Materials	These materials have native support from additive manufacturing (AM) equipment vendors, and many already have ASTM specifications that dictate powder/wire chemistry and use.	Incorporation into ASME BPVC, characterize environmental effects, & regulatory acceptance - EPRI led project submitted ASME Section III Data Package & Code Case for LPBF 316L in 2020 (EPRI Report 3002018273).
Materials Not in AM Marketplace	These materials are of interest to nuclear designers, but are not yet commonly used in the AM industry	Develop build parameters, feedstock materials specifications, incorporation into ASME BPVC, characterize environmental effects, and regulatory acceptance
Feedstock Quality Guidelines	Quality of AM-fabricated parts relies on incoming feedstock quality	Develop and publish consensus guidelines so additive manufacturers can adopt these best practices and flow them down to their feedstock suppliers and adopt feedstock handling procedures
Fatigue Data for As-Printed Surfaces	Surface finish significantly affects fatigue performance, but ASME Boiler & Pressure Vessel Code (BPVC) fatigue curves are primarily based on data generated from smooth bar specimen. With the desire to use AM parts in the as-printed condition, BPVC fatigue data may be non-conservative for these parts. Research is needed to understand the relationship between BPVC data and as-printed AM parts.	Develop material and process-specific fatigue curves or knock-down factors that can be applied to ASME BPVC fatigue curves
Powder Bed Fusion (PBF) Guidelines	Technical basis is needed for standards and guidelines for construction of components by the PBF process.	EPRI is working with the ASME BPTCS/BNCS Special Committee on AM for Pressure Retaining Equipment since 2017 to develop guidelines for control of PBF processes to fabricate and test AM pressure-retaining components
Directed Energy Deposition (DED) Guidelines	Technical basis is needed for standards and guidelines for construction of components by the DED process(es)	The ASME BPTCS/BNCS Special Committee on AM for Pressure Retaining Equipment has started work on a similar document (or revision to the PBF Guidelines) for DED processes
Essential Parameters	Various stakeholders & standards community have issued their lists of essential variables, but all of these lists differ. There is a need for industry consensus on the minimum list of essential parameters	Expert elicitation to ensure the full set of essential variables is defined, but limited to only those that truly affect the mechanical or critical properties of the finished part
Processing and Heat Treatment Requirements	There is a lack of industry consensus regarding the need to require hot isostatic pressing (HIP) and solution anneal (SA) for safety-related parts. These processes have been shown to improve material performance, but add time and cost to the product development and production processes.	Perform detailed studies comparing microstructure, mechanical properties and defect inclusion of AM components/builds with and without the HIP step performed
Technical Basis for Defect Acceptance Criteria	Define technical bases for the disposition of defects once found, whether using in-situ monitoring or ex-situ characterization - There is also a need to understand the types and locations of high-likelihood defects in AM-produced parts, including where and how such flaws might be expected to develop and grow in service.	Develop engineering bases by intentionally generating defects in ASTM E8 round bar tensile specimens, ASTM E466 fatigue specimens, and ASTM E399 compact tensile specimens
NDE Improvements for AM Parts	X-ray computed tomography (CT) is a powerful technique for detecting defects in AM parts, but there are limitations, including: - Large parts and thick wall sections are a challenge, time and cost, influence of surface roughness, multi-material attenuation, complex geometry, complex grain structure, etc. on pore/defect results	- Study current state-of-the-art in CT and other promising technologies - Build on ASTM E3166-20e1, Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build
Guidelines for NDE of DED Parts	There is an absence of predictive models that address the relationships between DED process, component geometry, and the resulting microstructure. Therefore, part quality currently needs verified through detailed non-destructive examination - Particular techniques are best suited for different points in the DED AM process (intra-layer, post build, post-processing)	Provide guidance to additive manufacturers in selection of the most appropriate NDE methods to use in each stage of a DED build.
ASME Code NDE Inspection Scope	ASME code currently treats all AM material as produced by a special process, subjecting entire component volume to extensive pre-service and in-service inspections	Develop ASME rules that limit NDE requirements to critical areas of the component or build volume, making initial and in-service inspections less burdensome
In-situ Real-Time Build Health Monitoring	AM components tend to be geometrically complex and difficult to examine post build where the defects of primary concern to AM (e.g., lack of fusion, porosity, and poor microstructure) are difficult/impossible to detect with current NDE techniques. - In-situ NDE can be used as a real-time check for process drift, closed-loop control, & quality records in place of post-build NDE.	- Review current state-of-the-art for reliable in-situ NDE techniques - Work with standards bodies and regulators to develop pathways that permit closed-loop control and/or use of in-situ NDE records to meet inspection requirements
Recommended Practices for Purchasing AM Parts	As AM-produced parts become more widely accepted, utilities will want to procure AM parts on a contract basis. There is a need for procurement guidance in two areas: (1) Model audit checklists to be used by nuclear procurement organizations, including industry consortia, such as NUPIC and NIAC and (2) Guidelines for procurement specifications.	- Review available procurement best practices within nuclear and other industries - Develop a model Quality Assurance checklist - Develop a guideline of technical topics to be addressed in purchasing specifications

Download the Full Report:
3002018276 - Advanced Nuclear Technology: Additive Manufacturing Roadmap for the Nuclear Power Industry

The Electric Power Research Institute, Inc (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI members represent 90% of the electricity generated and delivered in the United States with international participation extending to nearly 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; Dallas, Texas; Lenox, Mass.; and Washington, D.C.

Together…Shaping the Future of Energy™

3002022977

EPRI

3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com