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SURVEY OF PRE-SERVICE AND IN-SERVICE NONDESTRUCTIVE EVALUATION TECHNIQUES OF AMT-FABRICATED COMPONENTS

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Prepared in response to Task 1B in NRC Advanced Manufacturing Technologies Action Plan, Revision 1 (ADAMS Accession No. ML19333B980), by:

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Summary

The Pacific Northwest National Laboratory (PNNL) was contracted by the U.S. Nuclear Regulatory Commission (NRC) to perform a literature survey of the current state of the art of non-destructive examination (NDE) of components made using advanced manufactured technologies (AMTs). The main objective of this report is to provide NRC staff with an analysis of knowledge gaps and recommendations focused on current inspection and NDE methods that may be applied to AMT-fabricated components. In particular, this report focuses on NDE methods that can be used for pre-service inspection (i.e., as fabricated) and in-service inspection of AMT components.

AMTs are being used globally in many industries, including aerospace, automotive, medical, consumer products, and energy, to quickly and accurately manufacture components. There has been increasing interest in the use of AMTs in the nuclear power industry driven primarily by both the cost and convenience of components fabricated from AMTs. A key step in using AMT-fabricated components in nuclear plants will be the assurance that these components meet the quality and performance requirements of the industry and the regulatory authorities. AMT materials provide unique inspection challenges. For example, porosity and surface roughness are common issues with AMT components. Grain structures in AMT components have been well-studied and are typically larger than grains in wrought stainless steel and approximately the same size as grains typically observed in austenitic welds. Grain structures can be changed to more equiaxed by heat treatment, but there is a lack of data on the effects of AMT grain structures on ultrasonic testing signal-to-noise, scattering, and attenuation. As the nuclear industry progresses toward the use of AMT-built reactor components, it is critical that the inspection capabilities needed to qualify and monitor the integrity of these components are effective and reliable.

This report summarizes common AMT defect types, as well as the potential NDE techniques to detect such defects. The advantages, disadvantages, and limitations of the various NDE methods are also discussed. This report identifies the anticipated key challenges and knowledge gaps for pre-service and in-service NDE of components fabricated with AMTs, including gaps in the applicable codes and standards. From reviewing the literature in preparation of this report, 21 significant knowledge gaps that are relevant to NDE of AMT components and the related ASME inspection code are identified and ranked. These challenges and gaps are ranked from high to low priority from an NDE perspective based on the anticipated ASME Code requirements for applying pre-service and in-service NDE to AMT materials in nuclear power plants. PNNL subject matter experts relied on their combined experience in NDE research, in-service inspection, and ASME Boiler and Pressure Vessel Code to formulate the rankings.

Acronyms and Abbreviations

AE	acoustic emission
AI	artificial intelligence
AM	additive manufacturing
AMT	advanced manufacturing technologies
ASME	American Society of Mechanical Engineers
ASNT	American Society for Nondestructive Testing
ASTM	ASTM International (formerly American Society for Testing and Materials)
BNCS	Board on Nuclear Codes and Standards
BPTCS	Board on Pressure Technology Codes and Standards
BPVC	Boiler and Pressure Vessel Code
BWR	boiling water reactor
CASS	cast austenitic stainless steel
COD	crack opening displacement
CS	cold spray
CT	computed tomography
DED	directed energy deposition
DOE	Department of Energy
EB-PBF	electron beam powder bed fusion
EBAM	electron beam additive manufacturing
EBM	electron beam melting
EBW	electron beam welding
EBF^3	electron beam freeform fabrication
EPRI	Electric Power Research Institute
ET	eddy current testing
FMC	full matrix capture
HIP	hot isostatic pressing
HPCS	high pressure cold spray
IR	infrared
ISI	in-service inspection
ISO	International Organization for Standardization
ITER	International Thermonuclear Experimental Reactor
LOF	lack of fusion
L-PBF	laser powder bed fusion
LPB-AM	laser powder bed additive manufacturing
LPCS	low pressure cold spray
MT	magnetic particle testing

NASA	National Aeronautics and Space Administration
NDE	non-destructive examination
NEET	Nuclear Energy Enabling Technologies
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PBF	powder bed fusion
PM-HIP	powder metallurgy-hot isostatic pressing
PNNL	Pacific Northwest National Laboratory
POD	probability of detection
PSI	pre-service inspections
PT	penetrant testing
QA	quality assurance
RT	radiographic testing
SHM	structural health monitoring
SLM/S	selective laser melting/sintering
SME	subject matter experts
SMR	small modular reactor
SNR	signal-to-noise ratio
TFM	total focusing method
TG	Task Group
UT	ultrasonic testing
VT	visual testing
WAAM	wire arc additive manufacturing

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1.0 Introduction

1.1 Purpose

The purpose of this report is to provide the U.S. Nuclear Regulatory Commission (NRC) staff with information to assess the capabilities of the currently available inspection and non-destructive examination (NDE) methods to evaluate components fabricated using advanced manufactured technologies (AMTs). The AMTs of interest for this report are powder bed fusion (PBF), directed energy deposition (DED), electron beam welding (EBW), and powder metallurgy-hot isostatic pressing (PM-HIP). A discussion of cold spray (CS), an additive manufacturing method primarily used for overlays and repairs, is also included. This report evaluates knowledge gaps focused on the issue of whether NDE methods are capable of detecting the types of manufacturing defects anticipated in AMTs that may compromise the safe performance of the component. In particular, this report focuses on NDE methods that can be used for pre-service inspection (PSI, i.e., as-fabricated) and in-service inspection (ISI) of AMT components. It is feasible that components manufactured with AMT will need different levels of inspection compared to those manufactured with conventional methods. However, it is not the purpose of this report to discuss or differentiate which AMT components will require inspection or what that inspection should entail. Common AMT defect types are identified, as well as the potential NDE techniques to detect such defects. The advantages, disadvantages, and limitations associated with the various NDE methods are also discussed, in addition to whether differences in examination techniques are warranted based on the type of AMT. This report also explores gaps in the qualification and acceptance standards for the various techniques and identifies needed developments in codes and standards for examination of AMT parts.

1.2 Background

AMTs are being used globally in many industries such as aerospace, automotive, medical, consumer products, and energy to quickly and efficiently manufacture components. There has been increasing interest in the use of AMTs in the nuclear power industry as an alternative to conventional manufacturing processes. This interest is driven primarily by the cost and convenience of components fabricated from AMTs. The average age of nuclear power plants (NPP) in the United States is about 40 years. As NPPs continue to age, it is anticipated that there will be difficulty in obtaining replacements for some components, including some safety-critical components, due to loss of original equipment manufacturers over the years or to timeliness and cost considerations for developing certain components.

AMTs have the potential to benefit the nuclear industry by producing high-quality components more rapidly and less expensively than conventional fabrication methods. Certain AMTs, such as cold spray, may also be used for repairs. These benefits can be realized in at least two scenarios. First, AMTs may be used to provide precision replacements for components that are difficult to obtain due to reduction or loss of supply chain capabilities. The ability of some AMTs to fabricate a wide range of component types and sizes relatively quickly can support the need for suppliers to adapt to the unique challenges of fabricating components for the existing NPP fleet with cost effective approaches. These challenges include adopting high-quality standards while producing a low volume of unique components. Second, AMTs allow for fabrication of components in support of advanced reactor designs that might not otherwise be feasible. The design of advanced reactors can include components with complex geometries that may be costly or impossible to produce using traditional fabrication methods. Furthermore, the option to produce components with specialized characteristics, like microstructural features or imbedded inspection or sensor devices, can become possible with the use of AMTs.

A key step in the application of AMTs to the fabrication of NPP components will be the assurance that these components meet the quality and performance requirements of the industry and the regulatory authorities. Industries such as aerospace and defense are already qualifying and allowing the use of components manufactured by AMTs. Although the nuclear industry lags other industries in adopting AMTs, many companies are pursuing AMT-fabricated components for use in NPPs, particularly in advanced future plants. These companies include Westinghouse, Rolls-Royce, GE-Hitachi Nuclear Energy, Framatome, BWX Technologies, NovaTech, Mainstream Engineering, and NuScale (Gandy 2018; Hull et al. 2019; Mayfield and Nichol 2019; Selekler and Landrey 2019). Several universities and national laboratories are also involved in AMT research for nuclear applications. Much of the funding for this research comes from the U.S. Department of Energy (DOE) Nuclear Energy Enabling Technologies (NEET) Advanced Methods for Manufacturing program and the nuclear industry.

ISI activities are essential for certain components to the safe operation of NPP systems and are conducted routinely on safety-critical components. These activities ensure that a plant is operated in accordance with the applicable design assumptions and intended functional requirements. The objectives of ISIs are to reveal any flawed conditions of pressure boundary components and their supports that might lead to failures. In particular, early-stage detection of service-induced degradation of the pressure boundary is targeted in order to prevent leakage or rupture. ISIs with respect to the current operating fleet mostly comprise NDE performed on components of the primary pressure boundary of the reactor coolant system.

The NDE methods employed during ISIs of the existing nuclear fleet have evolved over more than 40 years into an established practice with strong technical and regulatory backing. The maturity of the technology is reflected in Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC, referred to herein as “ASME Code”). Section XI, Division 1, entitled “Rules for Inspection and Testing of Components of Light-Water-Cooled Plants” provides the requirements for inspecting components using a variety of visual, surface, and volumetric NDE methods. The primary objective of these inspections is to use NDE to identify surface and volumetric defects and imperfections such as cracks, wear, corrosion, or erosion. Section XI describes the requirements for applying these technologies, the approaches to be used in planning and conducting inspections, and the training for the examination equipment and inspector. The requirements and processes used in the nuclear industry and embodied in the ASME Code are derived from the extensive experience with the materials, the environmental conditions, and the component performance data available from over half a century of NPP operations.

With the introduction of components fabricated using AMTs, the intent and aim of ISIs and the application of NDE methods must be assessed in light of the unique characteristics of AMT materials. The goal of safe, reliable, and economic plant operation should continue to be achieved with the use of AMT components and, therefore, the integrity and reliability of safety-significant AMT components will require demonstration through inspections. Critical to this demonstration will be establishing the pre-service component condition and assessing the evolution of the component condition during in-service lifetime. The application of NDE methods and techniques to components produced with AMTs will require establishing the requirements and processes to ensure confidence that these examinations will be able to properly characterize the state of the component.

The National Aeronautics and Space Administration (NASA) recently evaluated the challenges of using NDE methods to qualify and assess the integrity of additive manufacturing (AM)-fabricated components (Waller et al. 2014). These challenges include such areas as complexity of part geometry, lack of defined critical defect types and sizes, lack of physical NDE reference standards, lack of established inspection procedures or processes, and lack of probability of detection data. NASA concluded that NDE will play a vital role in supporting the advancement of AM. Closing the NDE technology and information gaps will require efforts in both the progression of NDE technologies themselves as well as building experience databases with component characteristics coming from AM.

The challenges identified by NASA are not unique to the aerospace industry. As AMTs are adopted by the NPP industry, the component manufacturers, the plant operators/licensees, and the NRC will need to appreciate the inspection challenges in order to monitor plant safety. The strategy to perform the research, development, and deployment to identify and overcome challenges and close gaps is not well defined because the industry is currently in the early stages of assessing the benefits and costs of moving to AMTs. Indeed, the first AMT component used in an NPP (in Slovenia)—an impeller for a fire protection pump—was manufactured by Siemens and installed in 2017.[1] The first AMT part used in an NPP in the U.S.—a thimble plugging device—was manufactured by Westinghouse and installed in 2020.[2] Much of the focus has been on the identification and evaluation of the technologies, such as PBF, DED, PM-HIP, and EBW to manufacture components that meet design requirements.

This report summarizes the efforts to identify the key challenges and knowledge gaps for pre-service and in-service NDE of components fabricated with AMTs. Also, a review of the applicable codes and standards is provided to evaluate the needs for updating or modifying existing codes and standards or establishing new codes and standards. These challenges and gaps are assessed and ranked from high to low priority from an NDE perspective based on importance for being able to apply pre-service and in-service NDE to AMT materials in nuclear power plants. Safety significance or regulatory aspects for plant operations were not considered.

1.3 Assessment approach

The preparation of this report included two major activities. First, a wide-ranging literature review was performed to establish the available information on AMTs, characterization of typical material or component defects, and the use of NDE technologies on AMT-fabricated components. Second, subject matter experts (SMEs) were engaged and results of the literature review were presented to them. These SMEs were tasked with performing an assessment of the challenges and technology gaps for PSI and ISI of AMT components using the existing NDE capabilities and the established codes and standards.

The literature search was conducted using common literature and report databases. These databases primarily included Scopus® and Google Scholar. Scopus (www.scopus.com) is a subscription-based abstract and citation database curated by Elsevier, and Google Scholar (scholar.google.com) is a freely-available database powered by Google. Some publicly available government and private-industry reports are not indexed on these databases but may be found through regular internet searches using keywords, the article title, authors' names, or a

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[1] https://www.3dprintingmedia.network/siemens-sets-another-milestone-first-3d-printed-part-operating-nuclear-power-plant/

[2] https://www.3dprintingmedia.network/westinghouse-electric-company-3d-printed-part-nuclear/

combination thereof. Most of the articles, abstracts, and reports found were available either through PNNL library subscriptions, through interlibrary loan, or were free and publicly available. References to many American Society for Nondestructive Testing (ASNT) and International Organization for Standardization (ISO) standards were found, but because the field of AMT is emerging, many such documents were still being developed at the time of this report and not publicly available. Well over 300 articles, reports, abstracts, and presentations were retrieved; these were briefly reviewed to determine relevance to the project. Nonrelevant articles were removed from the database, and relevant articles were reviewed and used to find additional material. Of the remaining items retrieved for this report, fewer than 10% were specifically targeted to the nuclear industry.

Following the collection of articles and documents from the literature review, this information was disseminated to PNNL SMEs in AMTs, in nuclear NDE, and in the application of relevant codes and standards. These SMEs were asked to identify typical defects of AMT materials and evaluate the application of NDE technologies used in the nuclear industry to such materials. They were also asked to evaluate the status of AMT-relevant NDE codes and standards. The review efforts were limited to the primary technologies that the NRC views as most relevant to NPP applications, namely PBF, DED, EBW, and PM-HIP. Due to a high level of interest in the nuclear industry, a discussion of cold spray, an additive manufacturing method primarily used for overlays and repairs, was also included. The strengths and weaknesses of NDE methods were cataloged, along with considerations associated with in-process, pre-service, and in-service NDE inspection of components from AMTs. Note a complete assessment of in-process monitoring is outside the scope of the report, but a brief overview is provided for completeness by identifying relevant NDE methods associated with AMTs.

The results of the SME review were used to develop a list of knowledge gaps in applying NDE to AMT components for NPP usage. The knowledge gaps were identified in areas related to the technologies and practices of applying NDE to components from AMTs and the applicable codes and standards. Once the knowledge gaps were identified, a priority ranking was assigned of high, medium, and low. The priority rankings reflect the importance of resolving the knowledge gap so that NDE inspections of AMT materials can be carried out with confidence that critical flaws can be identified.

2.0 Selected advanced manufacturing technologies

AMTs have revolutionized the way complex components are designed and manufactured, and they have several advantages over conventional "subtractive" manufacturing,[1] including the ability to: 1) produce near-net-shape[2] components with complex geometries, 2) create limited quantity parts efficiently and with design flexibility, 3) fabricate replacement parts with no existing supply chain, 4) manufacture products with novel designs that are simply not possible with conventional casting and subtractive methods (Gaynor et al. 2014; Gaytan et al. 2009), and 5) join thick sections in a shorter time than conventional welding with a single pass. Furthermore, various AMTs can be used to repair worn-out or damaged components in existing nuclear plants. Areas of AMTs pertinent to the manufacture of NPP components are additive manufacturing, near-net-shape manufacturing, joining/cladding, and surface modification/coating (Horn et al. 2019; Nichol 2019). Despite the advantages of AMT over conventional manufacturing, there are significant issues that should be better understood and addressed before widespread use of AMTs in NPPs is adopted. Foremost among these issues is understanding the manufacturing defects unique to the AMT processes. Understanding these defects is critical to defect detection, monitoring, and mitigation.

This section provides an overview of the AMTs of interest to the nuclear industry that fall within the scope of this report: PBF (an AM technique), DED (an AM technique), PM-HIP (a near-net-shape manufacturing technique), and EBW (a near-net-shape technique as well as a joining technique). A discussion of CS is also included. In addition, pertinent defects of each technique are discussed, laying the foundation for a discussion of NDE methods and knowledge gaps in Sections 3.0 and 4.0, respectively. Because the focus of this report is NDE of AMT components, the AMTs are described briefly herein; more details are available in the following review articles and reports: (Babu et al. 2018; Bourell 2016; Collins et al. 2016; Dass and Moridi 2019; DebRoy et al. 2018; Gandy et al. 2012; Grasso and Colosimo 2017; Hitzler et al. 2018; King et al. 2015; Körner 2016; Sames et al. 2016; Sharratt 2015).

2.1 Additive manufacturing

Metal additive manufacturing is broadly classified as powder bed fusion and directed energy deposition processes (Stavropoulos and Foteinopoulos 2018). Both the AM methods are briefly discussed.

2.1.1 Powder bed fusion

PBF processes use a thermal energy source, typically a laser (L-PBF) or an electron beam (EB-PBF), to selectively melt and fuse powders in a layer-by-layer pattern to build a three-dimensional part. The corresponding technologies are broadly known as selective laser melting/sintering (SLM/S). The PBF process enables manufacturing of a wide array of geometrically complex parts of near-net shape that contain features not possible with conventional subtractive manufacturing processes. Currently, PBF is commonly used to manufacture small-to-medium sized parts in aerospace, automotive, medical, and machinery

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[1] The process of removing material from a block to achieve the final 3D object.

[2] Net-shape refers to the shape or condition of the final AMT product. Near-net shape means that some additional machining or processing is necessary to achieve the final product. The blog at https://www.digitalalloys.com/blog/near-net-shape-manufacturing/ contains a discussion of near-net shape in additive manufacturing.

applications (DebRoy et al. 2018). For instance, in aerospace, a fuel nozzle of a jet engine was manufactured via L-PBF by GE aviation (Colosimo et al. 2018) and a combustion chamber for the Dragon 2 spacecraft was fabricated via L-PBF by SpaceX (Waller et al. 2014).

A schematic of the process is shown in Figure 2.1. The process is contained in an inert-gas environment for L-PBF or in a vacuum environment for the EB-PBF. The PBF process starts with spreading a thin layer of metal powder on a substrate plate using a roller or a blade. Then, the energy source scans over the deposited powder according to a pre-selected pathway, consecutively melting and fusing the metal powder to the substrate, leading to the formation of the first solid layer. After the completion of this step, the building platform is lowered by an amount equal to the layer's thickness, the roller deposits the second layer of metal powder on the top, then the energy source melts and fuses the newly deposited layer onto the previous layer. The process is repeated until the component is completed. Many variables, including powder characteristics, energy deposition rates, scanning rates, and processing parameters, control the quality of build (Carter et al. 2016; Gu and Shen 2009; Hanzl et al. 2015; Jinoop et al. 2019; Qi et al. 2009; Thijs et al. 2010; Van Elsen 2007). For instance, powder feedstock with a large fraction of pores will result in a build with higher porosities as compared to the powder feedstock with a small fraction of pores (Qi et al. 2009).

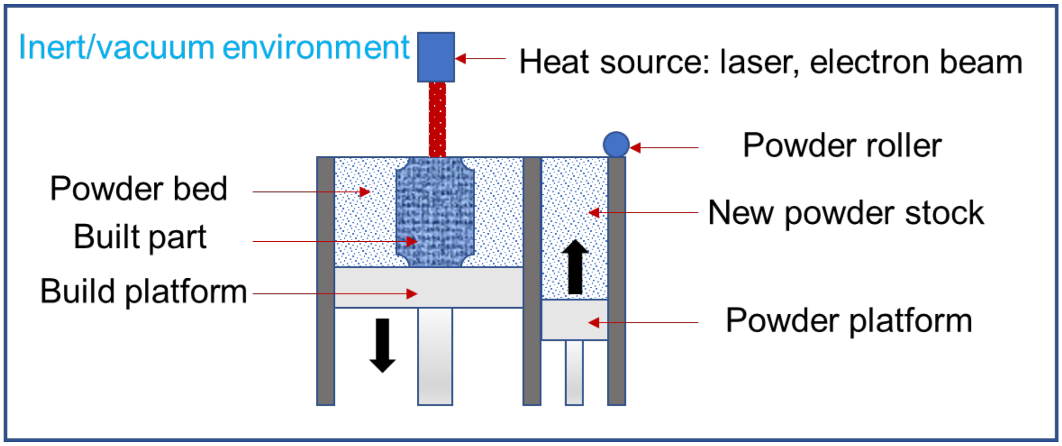

Figure 2.1 A schematic of PBF process

2.1.2 Directed energy deposition

Directed energy deposition (DED) employs a coaxial feed of powder or wire through a nozzle into an energy source (laser, electron beam, and plasma arc) to form a melted layer on a substrate (Figure 2.2). After the first layer, the nozzle head and the energy source are moved upwards to deposit the second layer. The process repeats until the 3D component is manufactured. DED is faster than PBF; however, it exhibits increased surface roughness and reduced feature resolution (measured by the width of deposition). The DED process is typically used for prototyping, low volume production of large, simple parts, and feature addition and repair. Wire arc AM (WAAM) employs an electric arc to melt a feedstock wire, and the melted bead is deposited on the substrate, creating a solid layer. The major benefit of WAAM is that larger parts can easily be manufactured as compared to the PBF process.

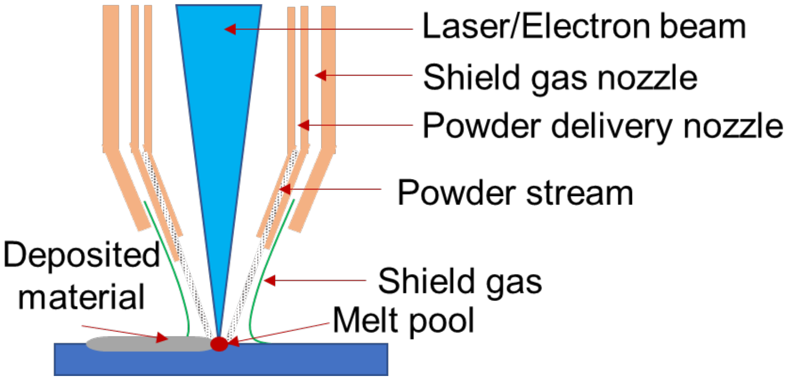

Figure 2.2. A schematic of DED

General microstructural characteristics of an AM (PBF or DED) component are elongated grains (also known as columnar grain structure) along the build direction, crystallographic texture, fine structure due to fast solidification, and segregation of certain alloying elements (Antonysamy et al. 2013; Babu et al. 2018; Collins et al. 2016). The presence of columnar grains typically results in anisotropy in mechanical properties along various directions. The formation of columnar grains can be avoided via process modification and the addition of inoculants such as carbides and oxides (Yan et al. 2017). Segregation is present due to the rejection of alloying elements at the solidifying interfaces. Various defects such as porosity, lack of fusion (LOF), surface roughness, cracking, and delamination were noted in PBF components. Furthermore, residual stresses and component distortion are commonly observed (DebRoy et al. 2018; Grasso and Colosimo 2017). Detailed information on common defects are presented in Section 2.6. Post-processing treatments are often performed to turn the as-built component into a usable end product, to modify the microstructure, and to improve the mechanical properties. Post-processing treatments such as stress relief, solution treatment and aging, hot isostatic pressing (HIP), and surface finish are done on a case by case basis (Sames et al. 2016). Thermal treatments are generally performed to relieve internal stresses and to promote the formation of equiaxed grain structure, thereby leading to reduced anisotropy in mechanical properties (Komarasamy et al. 2019a; Rebak and Lou 2018; Sames et al. 2016; Sharratt 2015). In the case of a precipitation-strengthened alloy system, aging heat treatments are typically carried out to increase the strength of the component (Komarasamy et al. 2019b; Sames et al. 2016). HIP is generally done to close any internal pores and cracks. As noted, surface roughness is a common occurrence; hence, surface machining may be done to obtain a smooth surface finish. HIP and surface finish treatments are known to improve stress corrosion cracking resistance and fatigue resistance (Fatemi et al. 2019; Masuo et al. 2018; Rebak and Lou 2018).

A process related to PBF is binder jetting, which lays a powder layer followed by a binder that is selectively deposited on to the powder, causing it to bond together to form the solid layer. After the completion of printing, the binder is either sintered or infiltrated with low-melting-temperature metal to reduce porosity and improve mechanical properties.

2.2 Electron beam welding

EBW is a welding process that uses an electron beam to directly melt and join the materials (Kim et al. 2016). EBW was developed in the 1950s, so it is a relatively mature AMT process. Filler materials, such as brazing rods or wire electrodes, are not used. The impingement of high energy electrons on the substrate results in a molten weld metal formation along the joint line, and subsequent cooling forms the joint (as illustrated in Figure 2.3) (Węglowski et al. 2016). The weld can be made in varying vacuum conditions such as high vacuum (10^{-3} to 10^{-6} mbar) to no vacuum (i.e., atmospheric pressure). EBW can weld thicknesses of 0.01 mm up to 250 mm (0.0004 in. to 10 in.) in the case of steel, and up to 500 mm (20 in.) for aluminum (Węglowski et al. 2016). EBW is a single pass, fast welding process; hence, there is a significant time and cost (>90%) savings as compared to other fusion welding processes. For instance, reactor pressure vessel girth welding of 110 mm (4.3 in.) thickness was completed in less than 60 minutes (Gandy and Stover 2018). The thermal efficiency of EBW is high, and a narrow weld with lower heat input leads to a low level of weldment distortion. The weld thermal effect on the base material is minimal; therefore, the heat-affected zone is narrow. Close tolerance between the abutting faces is essential because no filler material is added during welding. Post-weld heat treatment results in similar microstructure to the base material, which improves mechanical properties. Due to this, weld solidification microstructure related issues are avoided, thereby potentially reducing the weld inspection requirements (Gandy and Stover 2018). Major defects that may result from EBW are lack of penetration, weld metal cracking, gas porosity, residual stress, and voids or cavities caused by "spiking" (a sudden increase in penetration beyond what might be called the average penetration line) (Cottrell 1985). EBW is used in the following industries: automotive, aviation, medical, and railways (Węglowski et al. 2016).

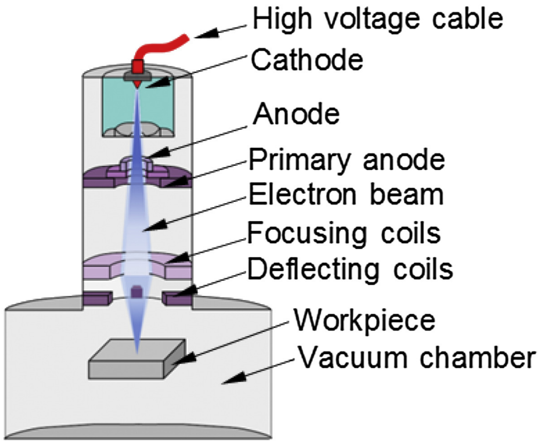

Figure 2.3 A schematic of the EBW process (Węglowski et al. 2016) Reprinted from Vacuum, 130, M. St. Węglowski, S. Błacha, A. Phillips, Electron beam welding – Techniques and trends – Review, Pages 72-92, Copyright 2016, with permission from Elsevier. https://doi.org/10.1016/j.vacuum.2016.05.004)

2.3 Powder metallurgy-hot isostatic pressing

PM-HIP is the process of compaction of encapsulated metal powders in a gas-tight container using high temperature and isostatic pressure (as shown in Figure 2.4) (Atkinson and Davies 2000). The combination of temperature and pressure can be used to achieve a density at a lower temperature than heating alone and at a lower pressure than cold isostatic pressing alone. It can produce large near-net-shape components, thereby reducing the materials and machining cost. PM-HIP is an efficient alternative route for long-lead time components produced via conventional manufacturing. The inhomogeneities in the starting powder material are eliminated during the HIP process due to diffusion. This process can be used with materials such as low melting temperature aluminum, high melting temperature iron- and nickel-based alloys, and a variety of ceramics. Examples of a few components manufactured via PM-HIP include a steam chest with internal cavities for steam turbine, an offshore oil valve body, and, for the International Thermo-nuclear Experimental Reactor (ITER), a blanket module (Mashl et al. 1999). Common defects are surface porosity, remnant internal pores, oxide inclusions, surface contamination, and surface roughness (Atkinson and Davies 2000).

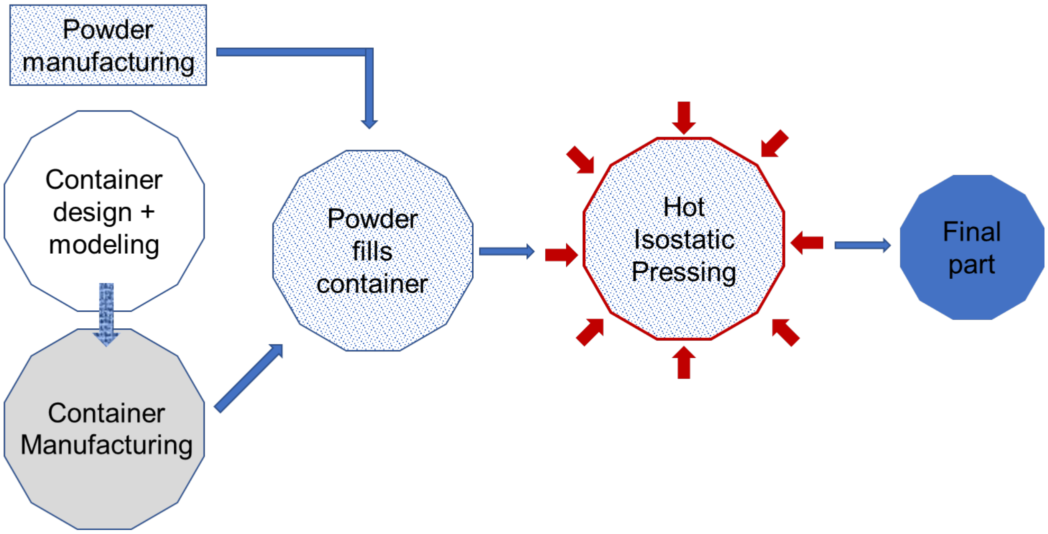

Figure 2.4 A schematic of PM-HIP

2.4 Summary comparison of the selected AMTs

Table 2.1 provides a brief summary and comparison of the different AMTs discussed above. The information presented here is based on the reviewed references and is not intended to be comprehensive.

Table 2.1 Comparison of selected AMTs

Attribute	PBF	DED	EBW	PM-HIP
Component size limitation	Small parts, approximately ~23 kg (50 lb)	Small to large parts, approximately 150 mm (5.9 in.) to multiple meters	Up to a plate thickness of 250 mm (10 in.) for steel and 500 mm (20 in.) for aluminum	~15000 kg (33000 lb) and up to 1.5 m (4.9 ft) diameter and 2.85 m (9.4 ft) height
Component complexity	Complex parts with high precision	Parts with less complexity	Welding configurations such as butt, Tee, corner, and end cap joints	Parts with less complexity as compared to PBF
Material systems	Metals (Ni-, Fe-, Al-, Cu-, Co-, Mg-, and Ti-based alloys), polymers, and composites		Metals (Ni-, Fe-, Al-, and Cu-based alloys and Ti)	Metals (Ni-, Fe-, Al-, and Co-based alloys) and composites
Possible post processing	Heat treatment, surface machining, and, in some cases, HIP		Heat treatment and surface machining	Heat treatment and surface machining
Common applications	Medical implants, automotive, aerospace, and prototyping		Nuclear, automotive, and aerospace	Steam turbine and oil and gas
Key microstructural characteristics	Columnar and equiaxed grain structure along the build and traverse build direction, respectively. Presence of segregation		Columnar and equiaxed grain structure parallel and transverse to the electron beam	Microstructural homogeneity with fine-grained equiaxed grain structure
Table references: (Aaltonen et al. 2009; Atkinson and Davies 2000; DebRoy et al. 2018; Gandy 2018; Kim et al. 2016; Liu 2017; Mashl et al. 1999; Town and Lawler 2015; Węglowski et al. 2016)				

2.5 Nuclear applications for component manufacturing

Of the AMTs discussed in this report, the one with the most mature development with respect to nuclear applications is PM-HIP (Town and Lawler 2015). One Section III Division 1 Code Case was adopted in 2013 for PM-HIP of 316L stainless steel.[1] Examples of components potentially applicable to nuclear applications manufactured via L-PBF, PM-HIP, and EBW are presented in Figures 2.5, 2.6, and 2.7, respectively. As discussed in Table 2.1, small and complex parts can be efficiently made with L-PBF. On the other hand, PM-HIP can fabricate near-net-shaped 406 mm (16 in.) diameter boiling water reactor (BWR) feedwater nozzles, as shown in Figure 2.6 (a).

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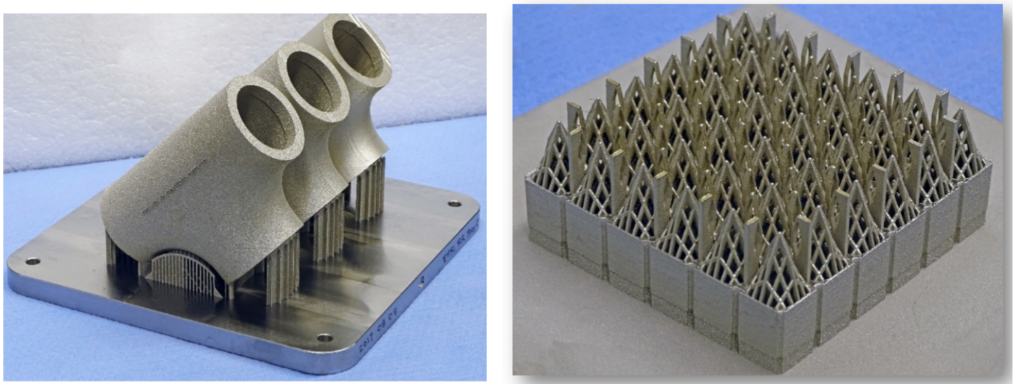
[1] ASME Code Case N-834, “ASTM A988/A988M-11 UNS S31603, Subsection NB, Class 1 Components.” This Code Case is listed in NRC Regulatory Guide 1.184, Revision 38 as being acceptable for use with no conditions.

A small modular reactor (SMR) upper head was fabricated to 44% size scale of the actual component as a single monolithic structure with 27 penetrations as a part of the DOE project DE-NE0008629 by the Electric Power Research Institute (EPRI) (Figure 2.6 [c]). Figure 2.6 (d) shows one-half of the lower reactor head manufactured by PM-HIP at ⅔ scale. A major limitation in fabricating full-scale components is the lack of availability of larger HIP facilities to manufacture larger components relevant to nuclear applications (Gandy 2015).



(a) (b)

Figure 2.5 Examples of components processed via L-PBF: (a) 316L SS pipe 50.8 mm (2 in. dia.) Tee-section and (b) Inconel 718 debris filter 76.2 × 76.2 mm (3 in.×3 in.). Image courtesy of EPRI, used with permission. (Hull et al. 2019)

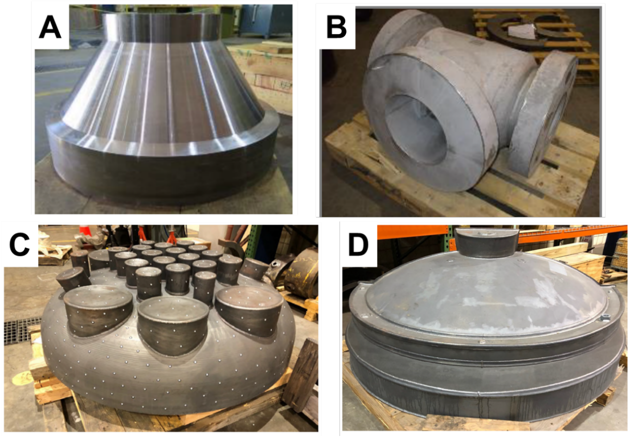


Figure 2.6 Examples of reactor component mockups produced by PM-HIP. (a) Near-net-shaped feedwater nozzle 406.4 mm (16 in. dia.) for BWR (b) 316L SS valve body (c) upper head (44% scale) made from two halves joined with EBW, and (d) one-half lower reactor head. Image courtesy of EPRI, used with permission. (Gandy et al. 2018)

EB welding of thick flange to the lower shell is presented in Figure 2.7. The weld diameter was ~1.8 m (6 ft) and the welding was completed in 47 minutes. Furthermore, one-half lower heads produced via PM-HIP (Figure 2.6 [d]) can be joined by EBW to produce the complete lower head. Overall, in addition to various advantages offered by individual AMTs, a combination of AMTs would lead to further improvement in the manufacturing of large/complex parts, as shown here.

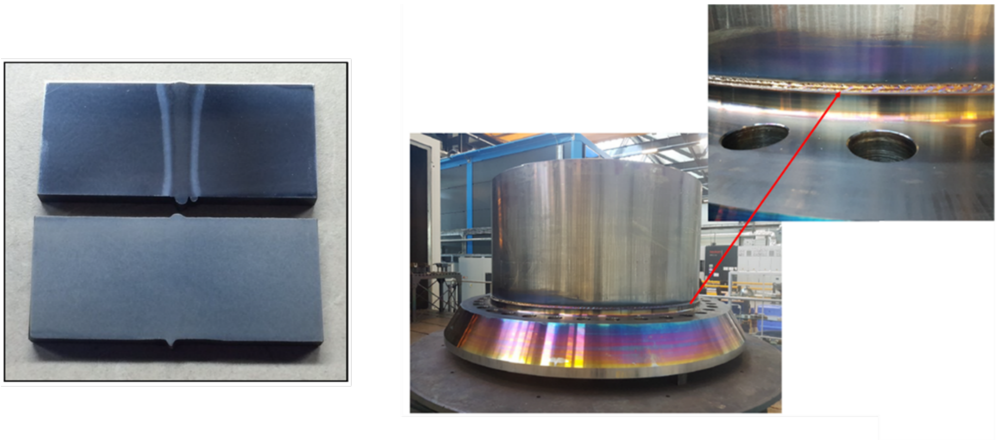


Figure 2.7 Examples of EBW. Left: an electron-beam weld before (top) and after (bottom) heat treatment. Right: Lower flange shell mockup with EBW, ~1.8 m (~6 ft) diameter, welded in 47 minutes. Image courtesy of EPRI, used with permission. (Gandy et al. 2018).

2.6 Common AMT defects

The quality and properties of AMT components are determined by the microstructural features, the defects, the residual stress states, and compliance with design dimensions. Ideally, the AMT parts should at least possess comparable, or preferably better properties than conventionally manufactured parts (Huang et al. 2019). However, the presence of defects in AMT parts is a major concern, limiting the wider deployment of AMTs in various industries. In the AMTs described above, feedstock attributes, processing parameters, and post processing treatments, if applicable, affect not only the resultant microstructural features, but also lead to generation of defects (DebRoy et al. 2018; Grasso and Colosimo 2017). Understanding the defects, especially their generation and mitigation, is critical for employing comprehensive monitoring and detection techniques. Furthermore, the defect fraction varies among the discussed AMTs. For instance, PM-HIP usually results in significantly lower defect fraction as compared to AM processes. Furthermore, wherever applicable, components manufactured via AM are subjected to HIP to reduce processing defects such as porosity and cracks. In this section, different types of defects will briefly be discussed, including microstructural and geometrical anomalies and undesirable residual stress states. Specifically, the nature, cause, and possible mitigating strategies for each defect will be presented.

2.6.1 Porosity

Porosity is a very common defect in AMT components. Although HIP can produce fully-dense components with no porosities (Gandy 2015; Mashl 2015), the final density of HIP components depends on the process parameters (Flodin et al. 2017). Porosities can originate from powder feedstock, can be processing-induced, and can be caused by solidification shrinkage related issues. The gas atomization process is known to entrap gases leading to the formation of spherical-shaped gas-induced porosity in feedstock powder, as shown in Figure 2.8 (a). These pores can be retained in the as-fabricated component, as shown in Figure 2.8 (c and e). Gas porosity cannot be completely eliminated by post-processing methods such as HIP (Bampton et al. 2005); hence, effective powder manufacturing and handling practices need to be followed. Powder manufacturing via a plasma rotating electrode process has been shown to eliminate gas-induced porosities in the powder (Figure 2.8 [b and d]) (Qi et al. 2009).

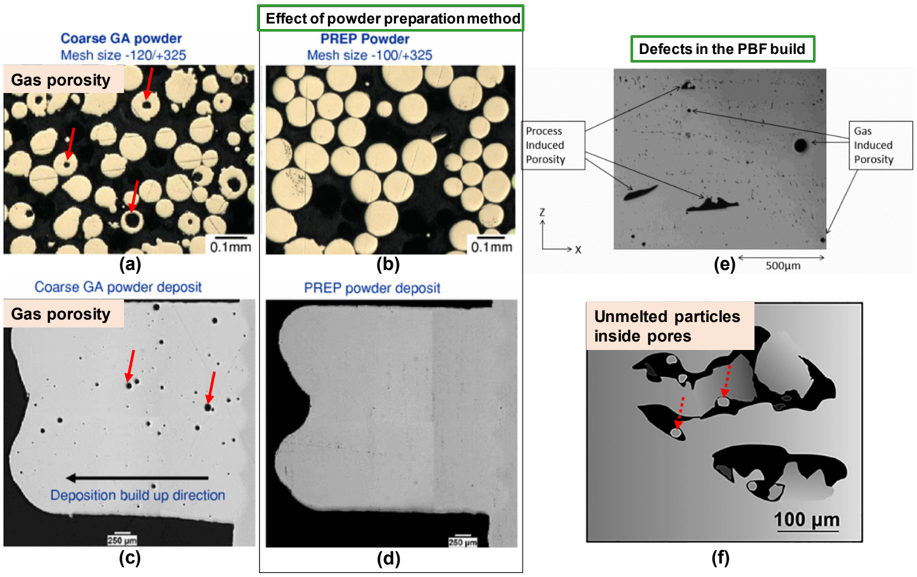


Figure 2.8 Gas porosity (marked by red arrows) in gas atomized (a) powder feedstock and (c) in as-fabricated build. Effect of powder preparation method showing the absence of gas pores in (b) powder feedstock and the (d) build (Qi et al. 2009). (e) Comparison of gas-induced porosity and process-induced porosity (Sames et al. 2016), and (f) presence of unmelted particles in the pores (Sola and Nouri 2019). (Figures a-d reprinted by permission from Springer Nature Customer Service Center GmbH: Springer Nature. *Metallurgical and Materials Transactions A*, "Studies of Standard Heat Treatment Effects on Microstructure and Mechanical Properties of Laser Net Shape Manufactured INCONEL 718," H. Qi et al , 2009, https://doi.org/10.1007/s11661-009-9949-3. Figure f reprinted by permission from Wiley Materials, https://doi.org/10.1002/amp2.10021.)

Processing-induced porosities in AMTs are mainly due to either low or high energy input. In the case of low energy input (e.g., if the laser power is low or the scan speed is high), incomplete melting of layers in PBF or EBW leads to the formation of LOF defects between adjacent layers. In PBF, the defects usually look like large irregularly shaped pores with unmelted particles inside, as indicated in Figure 2.8 (e and f) (Sames et al. 2016; Sola and Nouri 2019). The mitigation strategy is to increase the energy input to attain complete melting of the powder particles. LOF pores could be reduced by HIP. In the case of high energy input, a keyhole mode of melting will result in pore formation. High energy is sufficient to cause localized evaporation of the material. Keyholes are typically filled with ionized vapor produced during EBW or EB-PBF and may include some ambient gas used during L-BPF (Kim et al. 2016; King et al. 2014). Keyholes may be unstable even when the beam power and travel speed are well controlled because additional energy and localized pressure changes can result in partial collapse of the keyhole, forming large pores. A cross-section of a laser-melted PBF region showing the presence of a keyhole defect (marked by arrows) under two similar experimental conditions is shown in Figure 2.9 (King et al. 2014). The mitigation strategy for keyhole melting is to reduce the energy input. Furthermore, Marangoni flow—the mass transfer at an interface between two fluids due to surface tension gradients—can also entrap gases (Dass and Moridi 2019). For PM-HIP, near-surface porosities may persist, but they can be mitigated by surface machining or peening (Flodin et al. 2017).

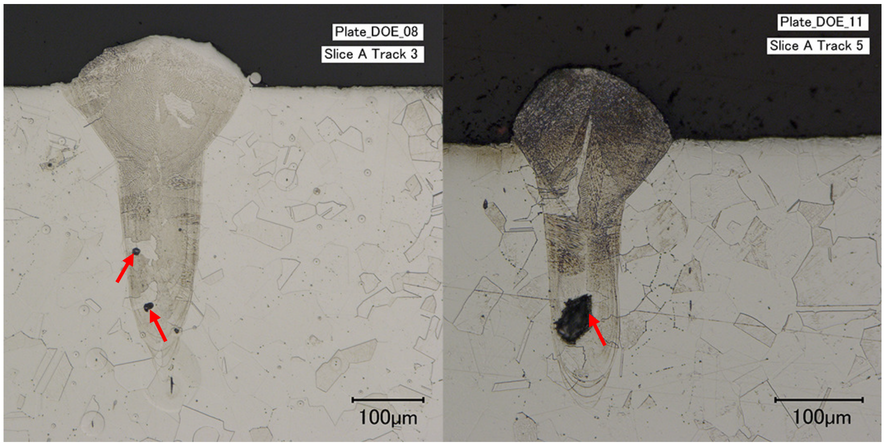


Figure 2.9 Keyhole void formation as marked by red arrows during laser melting (King et al. 2014) (Reprinted from *Journal of Materials Processing Technology*, 214 [11)] Wayne E. King, Holly D. Barth, Victor M. Castillo, Gilbert F. Gallegos, John W. Gibbs, Douglas E. Hahn, Chandrika Kamath, Alexander M. Rubenchik, "Observation of keyhole-mode laser melting in laser powder-bed fusion additive manufacturing," Pages 2915-2925, Copyright 2014, with permission from Elsevier.)

2.6.2 Chemistry deviation from original feedstock

For an alloy feedstock material, some elements are more volatile than others. When the molten pool temperature is very high (>1900 K) (Mukherjee et al. 2016), pronounced vaporization of those elements may occur, resulting in an overall deviated chemical composition from the feedstock material (Dass and Moridi 2019). This may happen when the alloying elements vaporize from the surface of the melt pool, ultimately resulting in depletion of those elements from the component. The surface area-to-volume ratio of the melt pool plays a significant role in the magnitude of the composition change. The redistribution of solute particles, which may melt at different rates or temperatures, from the layered heating and cooling process can also result in microstructural bands and local chemistry deviations (Dass and Moridi 2019). Changes in composition can also affect solidification microstructure, which may vary significantly from the desired state. Process control and composition adjustment to accommodate for vaporization loss could be employed as a mitigation effort.

2.6.3 Inclusions

Two types of inclusions can be observed in PBF components: 1) beneficial and 2) detrimental. In the case of beneficial, inclusions are added that serve as nucleation sites for grains leading to the formation of equiaxed grain structures, thereby resulting in improved mechanical properties. For instance, in the case of L-PBF of 7075 Al, addition of Zr inoculants resulted in crack-free deposits as compared to the 7075 Al builds that exhibited severe cracking. Pre-alloyed 7075 spherical powders coated with hydrogen-stabilized zirconium inoculants were used as the feedstock material (Martin et al. 2017). On the other hand, the processing material can chemically react with the shielding gas, resulting in the formation of oxide and sulfide inclusions (Taheri et al. 2017). In the case of 316L manufactured via L-PBF process, the presence of oxide inclusions in the size range of about 50 nm to 1 µm (2×10^{-6} in. to 4×10^{-5} in.) reduced the fracture toughness (Lou et al. 2018). Inclusions in PM-HIP samples were measured to typically be <1 µm (4×10^{-5} in.) in diameter and up to about 5 µm (4×10^{-4} in.) (Östlund and Berglund 2019).

2.6.4 Anisotropy

Structural evolution in any AM process is extremely complex due to the influence of various process variables such as scanning speed, power, spot size, and scanning strategy (DebRoy et al. 2018). By varying the process parameters, it is possible to obtain either elongated grains along the build direction or equiaxed grain structure. The formation of elongated grain structure is due mainly to the layer-by-layer nature of the fabrication process, and the presence of a compositionally similar previous layer leads to epitaxial solidification, where the solidification occurs via the growth mechanism on the partially melted grains of either the substrate or the previously deposited layer. The result of the epitaxial solidification is the formation of elongated, columnar grains as shown in Figure 2.10 (a). The columnar grains traverse multiple build layers, and the size of the melt pool in comparison with grain size can clearly be noted in Figure 2.10 (a). Figure 2.10 (b) shows an example of a few millimeters-long grains along the build direction in a Ti alloy processed via PBF. Columnar grains are generally observed in various alloys processed via PBF. Similar epitaxial growth and resultant columnar grain structure was also noted in EBW. A major issue with elongated grain structure is the resultant anisotropy in mechanical properties of the fabricated component because the transverse section perpendicular to the build direction exhibits comparably finer grains. In addition to processing control to achieve equiaxed grain structure, inoculants such as Zr in 7075Al alloy (Martin et al. 2017) are usually added to obtain equiaxed grain structure. In PM-HIP components, the grain structures tend to be fine-grained equiaxed with typical grain sizes of approximately 20 µm to 100 µm (8×10^{-4} in. to 4×10^{-3} in.) (Gandy 2015; Gandy et al. 2012; Hjorth 2007; Östlund and Berglund 2019).

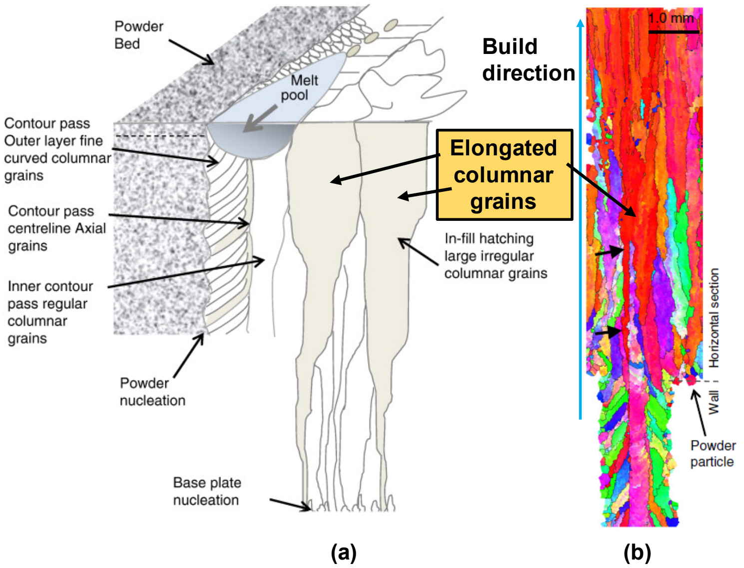
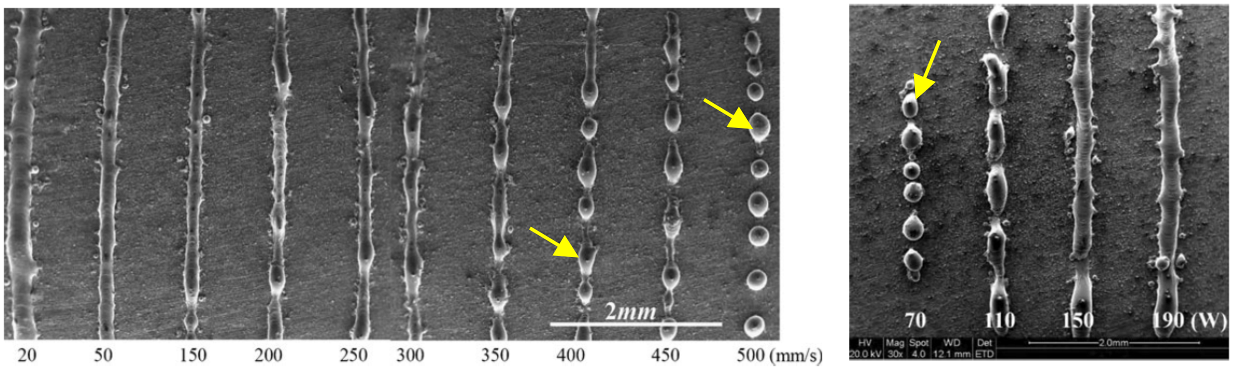


Figure 2.10 A general observation of columnar grain structure formation in various alloy system processed via AM processes is presented. (a) Schematic of columnar grains and (b) microstructure example of columnar grain in a Ti alloy. Note that the grain size along the build direction is larger than the melt pool that forms the layer-by-layer build. (Antonysamy et al. 2013).

2.6.5 Balling

In L-PBF, a balling effect, characterized by the presence of micron-sized particles and/or a discontinuous melt pool formation (as marked by arrows in Figure 2.11), is due either to the coarsening of spherical-shaped particles or to limited liquid formation (Taheri et al. 2017). Balling consists of un-melted particles and solidified spheres, and is due to the unstable melt pool; it is not inclusion particles. Several factors can result in balling. A sub-critical energy density can cause insufficient materials to exist in the liquid phase. Higher scanning speeds have also been attributed to instabilities in the molten pool due to the capillary effect. Oxide formation on the solid or molten material due to the presence of oxygen in the build chamber can change the wetting process and lead to balling. The effects of both scan speed and laser power on the balling phenomena is presented in Figure 2.11. The balling could affect the uniform distribution of the next powder layer and could also increase the surface roughness on the build. Optimizing the processing conditions, such as scan speed and power, in addition to reducing the oxygen content in the chamber could be suitable mitigation strategies (Li et al. 2011).



(a) **(b)**

Figure 2.11 Balling characteristics (marked by arrows) as a function of (a) scan speed and (b) laser power (Li et al. 2011). (Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature. *The International Journal of Advanced Manufacturing Technology*. “Balling behavior of stainless steel and nickel powder during selective laser melting process,” Ruidi Li et al, 2011, https://doi.org/10.1007/s00170-011-3566-1.)

2.6.6 Cracking and delamination

Solidification cracking, liquation cracking, and delaminations are common in PBF and EBW. (Simpson et al. 2019). Solidification cracking occurs along the grain boundaries of the build. Temperature variations and thermal cycling between build layers are significant (Dass and Moridi 2019; DebRoy et al. 2018). This difference leads to local tensile stress, with cracking occurring when the tensile stress exceeds the strength of the solidifying metal (Figure 2.12 [a]). Substrate preheating assists in reducing the extent of solidification cracking in alloys that exhibit severe propensity to cracking. Furthermore, formation of equiaxed grains is known to reduce the extent of solidification cracking. Liquation cracking is observed in the partially melted zone. This is mainly due to the melting of low-melting-point grain boundary phases. This cracking can occur in materials that exhibit large differences between the solidus and liquidus temperatures, have large melt pools due to low thermal conductivity, and have large coefficients of thermal expansion. Interlayer delamination occurs when: 1) the residual stresses are larger than the interlayer yield strength of the material and the layers separate, and/or 2) the presence of LOF defects lowers the strength of the interlayer (Figure 2.12 [b]).

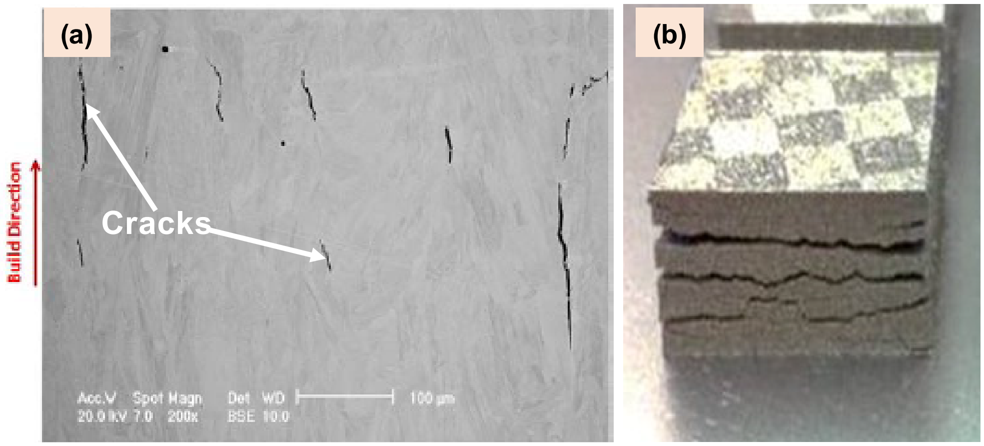


Figure 2.12 Examples of (a) grain boundary cracking and (b) layer delamination fabricated via PBF (Sames et al. 2016). The extent of cracking depends fundamentally on the alloy composition. For example, alloys that cannot be fusion welded will have solidification cracking issues in the build component. Therefore, composition or process modifications are generally carried out to reduce cracking or defects in the builds.

2.6.7 Residual stress/substrate warping

In PBF, DED, and EBW processes, the liquid metal is in contact with the relatively colder substrate of the previously deposited layer. This typically leads to a steep temperature gradient and subsequent thermal stresses, thermal strain, and residual stresses. The residual stress can distort the component, cause cracking along the grain boundaries, or lead to the delamination of the deposited layers (DebRoy et al. 2018). Furthermore, fatigue and fracture toughness properties of the components are also deteriorated by the presence of residual stresses. In addition to thermal stresses, volume change due to phase transformation upon cooling can also result in residual stresses and part distortion. A few potential ways to reduce residual stresses are substrate preheating, shorter deposition length, and smaller layer thickness. Variations in the scan pattern can also be used to reduce residual stress (Robinson et al. 2018).

2.6.8 Geometric anomalies: surface roughness and materials shrinkage

Surface roughness in AMT parts can arise from various material and process-related parameters, such as particle size, particle morphology, layer thickness, heat input, and scan speed (DebRoy et al. 2018). The presence of partially melted particles, balling, and LOF defects contribute to the surface roughness of the component. During low heat input processing, the energy is not sufficient to completely melt and fuse the powder particles, thereby causing a rough surface. Surface roughness increases with the increase in layer thickness and average particle diameter. In general, the surface roughness can be reduced by increasing the heat input, decreasing the scanning speed, and using the optimum particle size.

2.6.9 Porosity in EBW: Beam oscillations

In the EBW process, the fraction and the size of the pores are controlled by the weld operating conditions such as beam oscillation. In EBW, porosity is generally due to dissolved gasses like hydrogen/oxygen or entrapped gas pockets between the joining surfaces. Therefore, an oscillating beam as compared to a static beam produces intense material mixing, thereby leading to the reduction in pore fraction and the average size of the pores. Additionally, in a static beam, pores are found at the weld root, while an oscillating beam dispersed the pores in the fusion zone. Furthermore, beam oscillation produced joints with fine grain size in low heat input weld conditions.

2.6.10 Summary

Table 2.2 summarizes the types of defects that are common in the AMT processes described above.

Table 2.2 Types of defects in different AMTs

Types of defects	Typical Size Range		PBF/DED	EBW	PM-HIP
Gas porosity	~1 µm	Cause	Entrapment of shielding gas during processing	Entrapped gases	N/A
		Mitigation	Optimization of processing parameters		
Voids	1-500 µm	Cause	Due to LOF or high energy density leading to formation of spatter	Voids or cavities A spike (sudden increase in penetration depth)	Micro-voids Grain boundary migration leaving isolated pores inside grains
		Mitigation	Optimization of processing conditions		Increase the HIP time
Anisotropy	Hundreds of micrometers to millimeter	Cause	Columnar grains along the build direction are a result of epitaxial growth	Columnar grains are a result of high welding speed and epitaxial growth	N/A as PM HIP results in homogeneous microstructure with equiaxed grain structure
		Mitigation	Modification to the scan patterns, substrate pre-heating, and addition of inoculants	Beam oscillations and low welding speed	
Cracking	A few micrometers to millimeter	Cause	Solidification and liquation cracking are caused by large differences in liquidus and solidus temperatures and the presence of low-melting point phases along grain boundaries in the heat affected zone. Residual stresses leading to delamination of deposited layers		Cracks are generally not observed
		Mitigation	Compositional modification and substrate pre-heating	Compositional modification	
Residual stress	N/A	Cause	Repeated thermal cycle during component building	Fast solidification rate	Internal stress Due to variability of part hardening from surface to the center of the part
		Mitigation	Optimizing the process conditions and substrate heating. Post processing heat treatment	Post weld heat treatment	Optimize the HIP conditions
Surface roughness	Tens to hundreds of micrometers	Cause	Presence of partially melted particles, balling, and LOF defects	N/A	High strength particles indenting and deforming the low strength containers
		Mitigation	Optimum powder characteristics, processing conditions, and post-processing heat treatments.		Use of high strength containers or post-process surface conditioning

2.7 Cold Spray

Cold spray (CS) was not included with the AMT processes above because it is a relatively new technology, with CS for near-net-shape AM of structural materials a nascent research area (Champagne ; Parmar 2020). Much of the CS development that has occurred over the last two decades was done by the U.S. Department of Defense for dimensional restoration and property improvements, such as corrosion and wear resistance, of military equipment. Application of CS is expanding beyond military applications to component repair and manufacturing in other sectors such as aerospace, medical, electronics. Indeed, because of strong interest in using CS with high strength and/or high temperature materials in the nuclear industry, the subject is included in this report. For example, CS coated ZIRLO® and Optimized ZIRLO™ cladding tubes, developed by Westinghouse, are currently being tested in Byron Unit 2 cycle 22 (Shah et al. 2018). CS is currently being investigated for repair and mitigation of environmental degradation for spent nuclear fuel storage canisters and various light water reactor components.

CS is a solid-phase metal spray process during which no melting occurs, typically used for dimensional restoration, corrosion repair, and component manufacturing in aerospace, military, medical, and electronics applications. Thermal spray, on the other hand, is a family of metal spray coating processes where particles are fully or partially melted during the process and re-solidified after impacting the substrate (VRC 2020; TWI 2020). The technical driver for CS development and commercialization was the avoidance of issues such as residual stress or oxidation that are associated with high heat input, melting, and resolidification that occur during thermal spray processes.

During CS, metal particles are carried by a heated gas stream that softens the metal and propels particles at high velocities; see Figure 2.13. The impact energy is high enough to bond metal particles to the surfaces they impact. Because it is a solid phase process, CS avoids oxidation, tensile residual stresses, and other detrimental effects typical of the high heat input and melting associated with thermal spray. CS can produce arbitrarily thick coatings with beneficial compressive residual stresses. Heat generation and high shear conditions upon impact produce mechanical interlocking and metallurgical bonding that results in excellent properties (Yin et al. 2018). Because melting and resolidification do not occur, tensile residual stresses are avoided. Some CS processes produce beneficial compressive residual stresses in and immediately beneath deposited material due to a peening-like effect of particle impact.

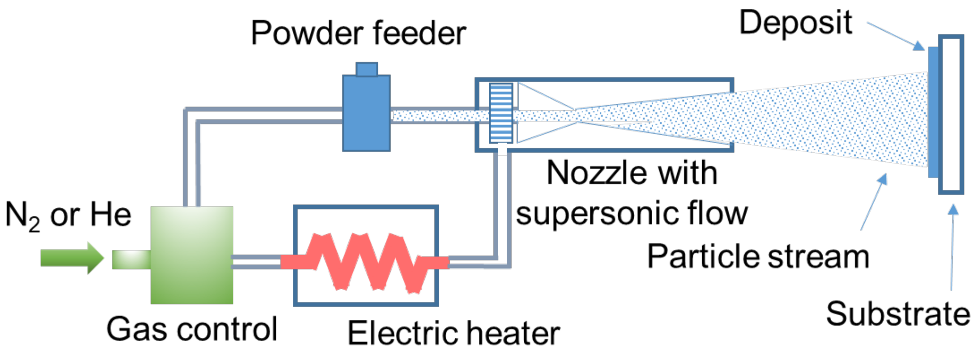


Figure 2.13 A schematic of cold spray

High-pressure cold spray (HPCS) is the metal spray process of greatest interest for CS additive manufacturing. Figure 2.13 shows a diagram of HPCS where particles are accelerated to supersonic velocities and impact a substrate. Figure 2.14 shows nickel deposited using HPCS. During the process, substrate heating is minimal, dimensional stability is maintained, and unwanted thermal effects (HAZ, thermal stresses, dilution layer formation, etc.) are avoided. HPCS systems operate at pressures typically ranging from 300 to 1,000 PSI (VRC 2020) and typically produce particle velocities ranging from 800 to 1400 m/s (Moridi et al. 2014). High velocity enables high kinetic energy, which is required to create high plastic deformation and shearing at particle surfaces. This results in dynamic recrystallization and metallurgical bonding at interparticle boundaries. Particles are held to each other and to the substrate by both mechanical interlocking and metallurgical bonding. HPCS is primarily achieved using Helium which imposes a significant cost burden. Helium recovery is a common practice to mitigate these costs in dedicated HPCS factory facilities but is more difficult for in situ applications.

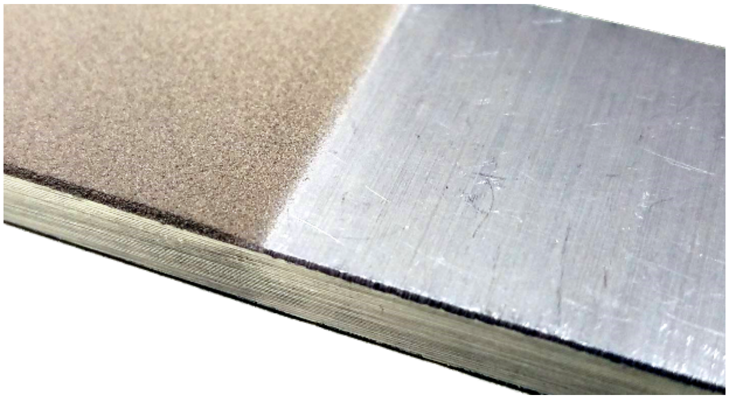


Figure 2.14. High-pressure cold spray coating of commercially pure nickel sprayed (left side) at PNNL.

Low-pressure cold spray (LPCS) is of lesser interest because it fails to propel particles fast enough to achieve the kinetic energy needed for high-quality cold spray deposition of alloys with high melting temperatures. LPCS systems operate at 300 PSI and lower (VRC 2020). They typically produce particle velocities ranging from 300 to 600 m/s (Moridi et al. 2014). Reduced kinetic energy associated with LPCS means less plastic deformation, less interlocking, and no or dramatically reduced metallurgical bonding in materials with high melting points. Reduced kinetic energy means deteriorated mechanical properties relative to HPCS. LPCS systems are not recommended for high-quality cold spray of steels, Inconel, and other high strength/melt temperature materials.

Kinetic metallization, pulsed gas dynamic spraying, vacuum cold spray, and warm spray are CS variants. These variants have not demonstrated the ability to match properties that can be achieved using HPCS for high melt temperature materials.

The primary defects in CS are caused by variations in process parameters, such as gas temperature, substrate temperature, powder size, powder oxidation or contamination, nozzle-to-surface distance, nozzle blockage, and powder impact angle. Parameter variations may cause significant defects, including porosities, voids, surface roughness, and poor surface adhesion (similar to lack of fusion). Some work using UT and ET has been done to detect and characterize CS defects, as described in (Glass et al. 2018); such studies are ongoing.

3.0 Inspection and NDE methods for AMT components

3.1 Introduction to relevant NDE methods for pre-service and in-service inspection

The primary factors that guide the selection and use of inspection methods in the nuclear power industry are reliability, effectiveness, safety, and cost. Methods, and the practitioners thereof, must be proven to be reliable and effective through the use of performance demonstrations. Consensus on the adoption of methods is required through ASME Code action. The process of establishing accepted NDE methods and techniques[1] is long and arduous, and for good reason: plant safety is at stake. Over the decades, only a few NDE methods have been approved for pre-service and in-service inspections. Personnel safety must always be observed, and inspection methods that may compromise safety, such as those that use ionizing radiation or require prolonged examination time (and therefore, excessive radiation dose) at the inspection site, are avoided. Cost is also a driving factor, including the cost of inspection equipment, the time to perform the inspection, and the time to analyze the data. These factors generally prevent the use of exploratory or experimental methods or even techniques that may be highly effective but require extremely expensive equipment or long set-up/take-down times. Although the literature may contain examples of promising new methods or techniques for NDE inspections, they are not commercially available, not practical for field application, or not incorporated into ASME Code for in-plant use (such as advanced phased array methods).

This section focuses on the most accepted and widely-used NDE methods for pre-service and in-service examination of nuclear components. Section 3.1.2 describes the different categories of NDE methods (i.e., volumetric, surface, and visual). A few additional potential emerging techniques will also be mentioned. Section 3.2 will discuss how these NDE methods can be applied to the AMT techniques that are within the scope of this report and were described in Section 2.0, namely PBF, DED, EBW, and PM-HIP. In general, the NDE method should be selected for an examination based on component geometry but also on the size, type, and location of the flaws that are likely to be present regardless of the manufacturing process that was used, be it casting, extrusion, or AM.

3.1.1 NDE methods used in the nuclear industry

The main NDE methods used in the nuclear industry today are ultrasonic testing (UT), radiographic testing ([RT] including x-ray and gamma ray), visual testing ([VT] which includes direct inspection and optical photography), penetrant testing (PT), eddy current testing (ET), and magnetic particle testing (MT) (USNRC 2012a). These methods have been tested, vetted, and used for decades and are well established in the ASME Code, which describes their use and applicability in pre-service and in-service inspections of NPP components. Acoustic emission (AE) testing (Eitzen and Wadley 1984) is an additional method that is used primarily during pre-service pressure or loading tests. Although AE has only been used once in the US, it has seen more use internationally (Hutton et al. 1982; IAEA 1999; Runow 1985). There are many excellent and detailed explanations and discussions of these NDE methods in the literature and how they can be applied to AMT components (not necessarily just in the nuclear industry) (Buddu et al. 2015; Gandy et al. 2012; Koester et al. 2017; Koester et al. 2018b; Kumar 2011;

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[1] In this report, “method” and “technique” are differentiated by the following: a method is the type of procedure being use, and a technique is the manner in which the method is implemented. For example, ultrasonic testing is a method and phased-array ultrasonic testing is a technique.

Lu and Wong 2017; Mandache 2019; Seifi et al. 2017; Sharratt 2015; Taheri et al. 2017). An additional method that is not used in nuclear NDE but is used in many other industries and will be discussed in this document is x-ray computed tomography (CT); CT is particularly applicable for evaluating small AMT components (du Plessis et al. 2018a; Koester et al. 2018b; NiPeijun 2000; Thompson et al. 2016). Note that the ASME Special Committee on Use of Additive Manufacturing for Pressure Retaining Equipment has identified VT, PT, MT, RT, UT, and CT as "available examination methods for additive manufacturing."[1]

3.1.2 Categories and descriptions of NDE methods

ISI methods are generally divided into three coverage categories by ASME Code, Section XI: visual, surface, and volumetric. Visual methods are capable of detecting visible surface-breaking flaws, or flaws that are open to the surface of the component. Note that the surface must be accessible to the examiner or to a remotely-controlled camera; surface-breaking flaws on the inner surface of a closed pipe will not be accessible yet are often the most important to detect. Surface techniques can detect flaws that are very close to the surface or surface breaking but not otherwise visible (note that PT requires flaws to be surface breaking). Volumetric methods can detect flaws throughout the entire volume of a component. For thin materials, such as heat-exchanger tubing, ET is essentially a volumetric method and can detect flaws throughout the thickness of the component wall. Volumetric methods are particularly useful for detecting flaws on inaccessible surfaces, such as the inner surfaces of pipes, or in regions where flaws may be likely, such as welds and weld interfaces.

Table 3.1 gives a brief summary of each NDE method.

Table 3.1 Summary of NDE methods: mode of action

NDE Method	Description	Category
UT (USNRC 2012e)	Uses high-frequency sound waves, typically in the range of 1–10 MHz. Cracks, porosities, inclusions, and geometrical features produce characteristic echo signals that can be detected and measured. Wall thickness, corrosion, and boundary layers can also be measured. Advanced UT techniques, such as phased array and full matrix capture (FMC) can be used to improve coverage, signal quality, and signal-to-noise ratio (SNR).	Volumetric
RT (USNRC 2012b)	Uses ionizing radiation from x-rays (x-ray tube) and gamma-rays, (typically from an isotope source such as iridium). Film, phosphor plates, or digital detectors can be used. Differences in material density from pores, inclusions, or cracks result in variations in image intensity that can be detected and measured. RT produces two-dimensional projection images, so depth information is not available.	Volumetric
CT[a]	Uses x-rays, typically from an x-ray tube. As with RT, material density variations are detected. In addition to volumetric information, CT generally provides better resolution and better contrast-to-noise ratio than RT. CT requires rotating either the tube/detector pair about the component or rotating the component so that multiple angles can be acquired. This is only practical with small components prior to installation and currently is not used in the nuclear industry.	Volumetric

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[1] BPTCS/BNCS Special Committee on Use of Additive Manufacturing for Pressure Retaining Equipment meeting minutes, October 30, 2019 (not publicly available)

NDE Method	Description	Category
VT (Cumblidge et al. 2004; Ramuhalli et al. 2018)	Uses visible light to detect surface-breaking flaws. VT is further broken down into subcategories of direct, remote, and enhanced. Direct visual involves examining a component without the aid of technology. Remote visual employs tools such as cameras or binoculars to inspect areas that are not accessible. Enhanced visual uses technological aids, such as high-resolution cameras or novel lighting approaches, to improve detection sensitivity. VT is the most common NDE method.	Visual (including direct visual, remote visual, and enhanced visual)
ET (USNRC 2012f)	Uses electromagnetic waves and an induction coil to induce currents in the component. The induced current is detected, and perturbations in the detected field may be indicative of a flaw. The penetration depth may be up to a few millimeters and is determined by the frequency, which is usually in the range of 20 kHz–1 MHz.	Surface
PT (USNRC 2012c)	Uses a low-viscosity dye penetrant and developer to reveal surface cracks. The penetrant is applied to the surface of the component and allowed to penetrate any cracks via capillary action. The component is cleaned, then the developer is applied, which draws the penetrant out and causes it to be visible on the surface. This is one of the simplest and most straightforward NDE methods.	Surface
MT (USNRC 2012d)	Uses magnetic particles and an applied magnetic field to reveal surface and near-surface discontinuities to a depth of up to 0.25 in. (6 mm). Magnetic particles are applied to the surface of the component, then the component is magnetized. Cracks perturb the magnetic field and cause the magnetic particles to align. This NDE method is very sensitive, but it can only be applied to ferrous components.	Surface
AE testing[b]	Uses acoustic sensors to detect crack growth, primarily during pre-service pressure, stress, or load testing. This method can be extremely sensitive to crack growth, but it does not find static flaws. Multiple sensors can be used to triangulate the position of flaw growth. This method is not common for in-service NDE.	Volumetric

[a] https://www.nde-ed.org/EducationResources/CommunityCollege/Radiography/AdvancedTechniques/computedtomography.htm

[b] https://www.nde-ed.org/EducationResources/CommunityCollege/Other%20Methods/AE/AE_Intro.php

An additional sub-classification of the NDE methods is whether the method requires direct contact with the component. In some circumstances, contact is not possible or practical. These circumstances may be governed by component temperature, potential occupational radiation exposure, access, cleanliness, or surface finish. Examination methods that require contact are: UT, PT, MT, AE, and ET (note that some ET exams may not require contact but still necessitate that the probe be in close proximity of the component surface). Certain UT techniques, such as laser UT or submersion UT, do not require direct contact. UT and ET are particularly challenged by complex geometries, because the probes must remain in contact (or near contact) with the surface. If, for example, surface curvature or roughness prevents the probe from maintaining contact, then the method will be inconsistent or ineffective. Contoured probes can be fabricated, and it is feasible to manufacture custom probe components using AM technology (Saboriendo et al. 2018). Non-contact methods are: VT, RT, and CT. For RT, the film or phosphor detection plates can be placed in direct contact with the component, but this is not necessary. In fact, the film or plates can be placed at a distance from the component in order to achieve image magnification.

3.1.3 NDE methods: strengths and weaknesses

The different NDE methods can be applied to any AMT component, depending on the types and locations of flaws that are being detected. However, the effectiveness of a given examination will be affected by specific component attributes, such as surface roughness, size, or shape. For example, rough surfaces that result from PBF or PM-HIP may prevent good contact with a UT or ET probe, so additional surface finishing would be required. However, surface conditioning could result in the obfuscation of any surface-breaking flaws that might be detected with VT. Table 3.2 summarizes the anticipated achievable resolution, the uses, and the strengths and weaknesses of the various NDE methods. The resolution is given as the order of magnitude of the smallest detectable flaw under favorable conditions. Actual flaw detection in the field will depend of various factors, such as surface condition or inspector skill. Specific AMT component properties should be considered when evaluating a method's strengths and weaknesses.

Table 3.2 Summary of NDE methods: strengths and weaknesses

Method	Resolution (order of magnitude)	Uses/Strengths	Weaknesses
UT	~1 mm, depends on the frequency used	• For detecting and measuring cracks, flaws, voids, corrosion, density, porosity, granular structures • Volumetric • Well established for PSI and ISI • No safety issues • Rapid, portable	• Not amenable to complex geometries • Smooth surface or surface conditioning needed • Requires highly-trained operators • Most in-service examinations use couplant and require direct contact
RT	~0.1 mm	• For detecting and measuring flaws, voids, corrosion, density, porosity • Little or no specimen preparation needed • Well established for PSI • High resolution • Permanent record	• No volumetric depth information • Requires highly-trained operators • Small flaws relative to specimen thickness are not detectable • Linear and planar flaws such as cracks and delaminations difficult to detect • Safety limitations due to ionizing radiation
CT	~0.01 mm	• For detecting and measuring cracks, flaws, voids, corrosion, density, porosity • Volumetric • Little or no specimen preparation needed • high resolution	• Expensive • Not portable • Requires highly-trained operators • Most relevant to small components • Not suited for ISI • Long scan times
VT	~0.01 mm COD* with optical magnification	• For detecting surface-breaking flaws • Inexpensive • Easy to implement	• Strongly affected by surface finish and lighting • Subjective to operator experience or opinion • Flaws must be surface-breaking

Method	Resolution (order of magnitude)	Uses/Strengths	Weaknesses
ET	~1 mm, depends on the frequency used	• For detecting surface and near-surface flaws • High sensitivity • Inexpensive • Rapid, portable • Can detect sub-surface flaws • Commonly used for thin-walled applications, such as heat exchanger tubing	• Affected by surface conditioning • Applicable only to metals • Requires highly-trained operators
PT	~0.001 mm COD*	• For detecting surface-breaking flaws that may not otherwise be visible • Inexpensive • Easy to implement • Can detect flaws that VT may miss • Applicable to a wide range of material types • Can be used on large areas	• Requires application of penetrant and developer • Strongly affected by surface conditioning, cleanliness, and roughness • Flaws must be surface-breaking • Tends to oversize rounded indications
MT	~0.001 mm COD*	• For detecting surface and near sub-surface flaws • Rapid • Inexpensive • Easy to implement • Can detect flaws that PT may miss • Surface preparation not as critical as for PT or VT	• Only applicable on ferrous (magnetic) materials • Requires wide application of particles • May not be practical for inspection of large parts
AE	~0.001 mm for crack growth, crack localization varies widely	• For pre-service detection of fabrication induced cracking • Extremely sensitive for detecting crack growth • Inexpensive • Ideal for large components	• Can be affected by environmental factors • Not currently used for in-service nuclear NDE • Imprecise for determining crack location • Requires highly-trained operators

*Crack opening displacement

Table 3.2 References: (du Plessis et al. 2018a; Ithurralde et al. 2001; Lopez et al. 2017; Lu and Wong 2017; Mandache 2019; Sharratt 2015; Stair and Moore 2019; Taheri et al. 2017; Thompson et al. 2016)

3.2 Considerations for in-process, pre-service and in-service inspection of AMT components

Pre-service and in-service inspections are required by ASME code on all safety-critical nuclear components. Pre-service examinations are governed by ASME Section XI in order to establish a baseline for future in-service examinations. Such inspections are done following the removal of any fabrication flaws that may have been identified and removed during the ASME Section III fabrication process.[1] Traditionally, RT has been applied for pre-service volumetric examinations, although Code Case N-831 now permits UT in lieu of radiography for some applications. PSI and ISI examination volumes focus on component surface areas where in-service flaws are known to originate, and both the PSI and ISI examination volumes differ from the Section III examination volume.

3.2.1 NDE for in-process monitoring

In-process monitoring is the process by which an AMT component is monitored via an NDE method during the build phase. There is a great deal of research being conducted on this topic, but a complete assessment of these technologies is outside the scope of the report. A brief overview is provided for completeness by identifying relevant NDE methods associated with ATMs. Separate reports would be required to comprehensively address in-process monitoring for each AMT. A large number of variables can be monitored during the build phase, including all aspects of the equipment as well as monitoring the component. One author describes over 50 variables to be monitored or controlled in selective laser melting, a PBF method (Van Elsen 2007). Another report lists over 20 quality control operations for the PM-HIP build process (Gandy et al. 2012). Because of the temperatures and speed of EBW, NDE in-process monitoring may not be practical, although one study was found where AE was applied during the EBW process (Dickhaut and Eisenblatter 1975). In-process monitoring of EBW may be done with VT or with multi-sensor ET or UT, but the process monitoring must guarantee the weld quality, a task that may be better suited for post-process NDE (Ithurralde et al. 2001). Additionally, the temperatures and pressures required for PM-HIP are not conducive to NDE in-process monitoring. Therefore, this section will focus primarily on in-process monitoring of PBF techniques. For excellent discussions of NDE in-process monitoring, see Sharratt (2015) and Lou et al. (2018).

In-process monitoring can play a critical role in AM quality, control, and throughput (AM-Motion 2018). The primary goal of in-process monitoring is to provide a preemptive quality assurance method to identify and mitigate build problems or component flaws before product fabrication has been completed (Chauveau 2018; Koester et al. 2018b). Much research has been done to develop and verify in-process monitoring because the potential pay-off is large. If a problem is caught, the build can be paused or terminated and the problem fixed, thus saving significant time and resources. Furthermore, monitoring the build process can help assure consistency, repeatability, and uniformity (Waller et al. 2014). In-process monitoring must be performed with non-contact methods so that the build process is not interrupted or compromised. The primary method for in-process monitoring is some form of VT, including wavelengths out of the optical range (Koester et al. 2018b; Sharratt 2015; Simpson et al. 2019; Waller et al. 2014). Other methods and techniques that have been used for in-process monitoring include laser UT, thermography, ET, and CT (Chauveau 2018; Mani et al. 2015; Sharratt 2015; Taheri et al. 2017); laser UT and thermography are discussed briefly at the end of this section. In-process monitoring would be especially beneficial for large builds that are time consuming and complex. Automated in-process monitoring has the potential to make flaw detection rapid and objective while reducing errors related to human factors. However, a potential problem is data management, particularly with large builds, because of the number of high-resolution images

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[1] ASME Section III governs NDE of new plant construction, or, in the case of a plant already in service, the repair/replacement of plant components. The examination requirements and acceptance standards are defined in ASME Section III NB-5000 with the objective to ensure a new component is free from flaws or conditions that could cause a safety or operational issue if placed in service. The examination volume, NDE method applied, and recording criteria differ from pre- and in-service inspection requirements.

that would need to be stored (Koester et al. 2018b). This data management problem could be solved with real-time analysis. In-process monitoring would also benefit from computer-aided or artificial intelligence (AI) detection algorithms (Gobert et al. 2018; Li et al. 2018; Okarma and Fastowicz 2020; Waller et al. 2014).

A goal of in-process monitoring is to render superfluous any PSI because the quality of the build has already been examined and assured (Waller et al. 2014). However, even if this goal is reached, any processes done after the initial build, such as heat treatment or HIP, will likely require additional NDE quality assurance (QA) inspections to verify that no new flaws were introduced or that known flaws were mitigated. In addition, AMT components, just like conventionally produced components, will still require pre-service pressure and stress testing to demonstrate that the component is sound and will serve its intended function.

3.2.2 Post-process and pre-service inspection considerations

Following the manufacturing process, all components must be inspected to assure fitness for service, regardless of the AMT process used. Such inspections should be conducted after completion of any heat treatments or hot isostatic press treatments. Section V of the ASME Code specifies and describes the NDE methods and techniques available for PSIs of conventionally manufactured NPP components. These include all the methods described above in Table 3.1 (except CT). It is important to note that many PSIs benefit from the fact that completed components not yet placed in a plant can more effectively accommodate inspection due to increased access. For example, piping internals can be accessed prior to welding the piping into place. In such cases, RT is often the most practical NDE method because the x-ray (or gamma ray) source can be placed inside the pipe (or conversely, the film can be placed in the pipe and the source outside) for single-wall exposures. Indeed, for conventional manufacturing, RT is commonly used to detect weld fabrication flaws, such as LOF, porosity, and inclusions. Recently, the ASME Code has approved UT in lieu of RT for repair/replacement inspections. RT can typically be done more rapidly and with higher resolution, but UT is preferred in situations where radiation poses an exposure risk to personnel. In such situations, all personnel must be cleared from the building, which means that all other work must stop during the RT exam. UT and RT are also sensitive to different types of flaws, with UT more sensitive to planar flaws (such as cracks) and RT more sensitive to volumetric flaws (such as porosity). Thus, the NRC continues to mandate the use of RT (and not UT) for ASME Code Section III exams of new construction as RT is sensitive to the types of flaws expected from fabrication. RT establishes a permanent record of the pre-service condition that can be referred to during ISIs (note that encoded UT establishes a permanent digital record, but many UT exams are not encoded). Additional PSI must be done after a component is installed in order to verify that the installation process did not introduce flaws; this is typically done using UT.

If CT is available, which would only be in a manufacturing facility, it is the best method for inspecting smaller parts (Colosimo et al. 2018; du Plessis et al. 2018b; NiPeijun 2000; Thompson et al. 2016). For example, CT has been used to examine porosity in parts joined with EBW (NiPeijun 2000); the pore quantities and sizes depended on welding speed but tended to average around 10 μm (4×10^{-4} in.) (Dinda et al. 2016). However, EBW is more typically inspected with VT, PT, UT, or RT.[1] Cost and size limitations likely prevent many EBW components from being inspected with CT.

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[1] https://www.ebpglobal.com/how-to-control-the-quality-of-electron-beam-welding/
https://www.ebindustries.com/weld-inspection/

3.2.3 In-service inspection considerations

ASME Code Section XI describes the methods currently allowed for ISI in NPPs. Most methods and procedures for ISI overlap with those of PSI. However, key differences arise during ISI primarily due to access restrictions. For instance, piping and component internals are generally not accessible during ISI. Component access is critical for inspectability, and limited access can result in truncated or skipped examinations that would require requests for inspection relief, no matter how the part was manufactured. In addition, the relevant flaws and inspection volume are different for pre-service and in-service inspections. PSIs are designed to detect weld fabrication defects, such as LOF, porosities, and slag inclusions. Therefore, the inspection volume includes the entire weld region from the outer surface to the inner surface. The defects of interest during ISI, on the other hand, are those that may be caused by service conditions, such as stress corrosion cracking and thermal fatigue cracking. For piping ISI, the required inspection region is usually restricted to the inner one-third volume of the weld region because operating experience has shown that flaws will originate at the inside component surface. The most commonly used technique for ISI of large components is UT. Thinner components, such as heat-exchange tubing, are inspected with ET.

Most ISI considerations with AMT components are anticipated to overlap with those of conventional components. The primary goal of ISI is to identify flaws that have developed during service. If a flaw is identified, a determination must be made to either monitor the flaw’s growth over time or to repair or replace the component. Specific guidelines are established in ASME Code Section XI for determining the course of action to take if a flaw is found. However, with AMT components, critical flaw types and sizes are not yet known because the method of manufacture differs from conventional components. Until it can be demonstrated that AMT components have the same critical flaw types and sizes, it cannot be assumed that they do. Furthermore, an AMT component may contain no welds, so the inspection volume cannot be defined in terms of weld regions. It should be anticipated that the current inspection guidelines for conventional construction and those developed for AMT components will diverge as more information and operational experience is gained with AMT. For example, if it is determined over time that AMT components require different inspection types, intervals, or volumes, then the inspection guidelines will need to be revised to reflect that. More must be learned about the response of AMT components to fundamental degradation mechanisms, the locations of critical defects within the component volume, and the long-term and service-induced effects of the different defect types. Such information will help define inspection volumes and intervals and provide the basis for the development of aging management programs. One potential advantage of AMTs in general, and PBF techniques in particular, is that components can be designed with inspection in mind, since there is essentially unlimited flexibility in component geometries (i.e., there are no casting or machining constraints).

3.2.4 Lifetime monitoring and structural health monitoring

Lifetime monitoring, structural health monitoring (SHM), and aging management all fall into the category of passive or observational NDE, primarily using AE sensing. SHM has been an active area of research for many decades (Runow 1985; Sharma and Sreenivas 2015). In addition, ASME Code Case N-471 has been approved for continuous AE monitoring of known flaws in certain conditions (IAEA 1999). For completeness, this report provides an introduction to the topic, and a separate report would be needed for a comprehensive discussion of SHM. Typically, a sensor is attached to or embedded in a component, and any changes that occur to the component over time can be recorded (Albakri et al. 2017; Fielding et al. 2016). For example, AE monitoring can detect acoustic bursts that occur during crack growth. AE should be done over long periods of time because crack growth is a slow and unpredictable process. Fundamentally, the long-term monitoring of AMT components is not expected to differ from that of conventional components. However, monitoring of AMT components such as those made by PBF may be enhanced if it is possible to implant probes or sensors during the build process (Sharratt 2015). The primary issue with embedded sensors is heat damage that would occur during fabrication, since the melting point of the powder or feedstock (>1000°C) is generally higher than the sensors can tolerate. Thermocouples may be most amenable to embedding, but they provide limited information that would be considered in the realm of NDE. Embedded sensors must be heat tolerant (due to the build process) and must withstand high pressures or temperatures of any post-build treatment, such as sintering or HIP. Also, any required wires or leads must pass through the material. If AMT-embedded sensors are feasible, it must be investigated whether the inclusion of sensors would compromise the material structurally or inhibit other NDE methods in the vicinity of the sensor. For example, if an embedded sensor masks a crack from UT insonification—perhaps a crack even caused by the inclusion of the sensor itself—then that crack may not be detected or may be mistaken for part of the embedded sensor. Significant drawbacks of SHM are that the same sensors should be permanently attached for the lifetime of the component and that SHM is subject to environmental and operational changes (Chauveau 2018). A great deal of research will likely be required if SHM using embedded sensors is pursued; some options are discussed in Section 7.11 of Sharratt (2015).

3.3 NDE methods applied to PSI and ISI of AMT components

There are several review articles and applications of pre-service NDE methods specific to AMT components; however, they are not necessarily specific to NPP components (Gandy et al. 2012; Ithurralde et al. 2001; Koester et al. 2018b; Kumar 2011; Lu and Wong 2017; Mandache 2019; NiPeijun 2000; Sharratt 2015; Taheri et al. 2017). These articles discuss post-process NDE methods for AMT parts, including descriptions of each process, advantages and disadvantages, and specific applicability to AMT flaws. A report by Simpson et al. (2019) very briefly discusses issues of post-process inspection of NPP reactor core components.

In the course of preparing this report, only a few articles or reports were found that directly addressed the issues of inspecting AMT components in an NPP-specific context, and these focused on PM-HIP (Gandy 2015; Gandy et al. 2012). Other industries, such as aerospace, have more mature applications of AMT parts and, correspondingly, more NDE-specific publications. Nevertheless, all of the NDE techniques described in Tables 3.1 and 3.2 that are applied to conventional NPP construction can also be applied to AMT construction. It is likely that existing ASME Code can be used as a basis for the methods of NDE examinations of AMT components. However, the critical defect types, sizes, and locations will likely be different. Furthermore, the periodicity of exams may be different, but more research and experience with AMT materials will elucidate what appropriate examination intervals are. Important gaps that have been identified in NDE of AMT are discussed in Section 4.0.

Table 3.3 summarizes the applicability of the different NDE methods to flaw detection in AMT components. Some degree of surface conditioning will likely be necessary for all methods except for RT or CT. Note that selecting an NDE method depends less on the advanced manufacturing technique used than it does on the component properties (such as geometry and composition) and the anticipated type and location of the defects.

Table 3.3 Applicability of the NDE methods to the AMT defects of interest

Flaw	Approximate Size range	NDE Methods	Notes
Porosity/Voids	1–500 µm	RT/CT/UT	RT and CT may not be sensitive to porosities that are small compared to the specimen thickness (~1%). Porosity may be hard to distinguish from grain effects with UT
Shrinkage/Dimensional Accuracy	≈1%	VT/CT	Shrinkage can be detected during final dimensional analysis. VT is only applicable to visible or external surfaces
LOF	100–400 µm	RT/CT/UT	RT is only sensitive to planar LOF that is parallel to the beam direction
Density variations	≈1%	RT/CT/UT	Density variations can be measured with good sensitivity. Little research was found in this area with regards to AMT
Surface roughness	28–80 µm Ra	VT/CT	The VT technique in this case is enhanced VT, as significant magnification is required
Inclusions	0.001–1 mm	RT/CT/UT	RT and CT may not be sensitive to inclusions that are small compared to the specimen thickness (~1%) or have densities comparable to the specimen's. UT may have difficulty distinguishing inclusions from grain effects.
Residual Stress	≤775 MPa	UT/RT/ET	X-ray diffraction RT is established but not used for NPP PSI or ISI. Some non-nuclear applications of UT and ET exist.[1]
Interior Cracks	.001 - 1 mm	UT/ET/VT/PT/MT/RT	VT and PT are applicable to surface-breaking cracks, ET and MT may be applied to surface or near-surface cracks, and RT may detect cracks with favorable orientation
Surface flaws	wide range, depends on type of flaw	ET/VT/PT/MT	Detection of surface flaws may be hindered by surface roughness or conditioning

[1] For example, see https://www.veqter.co.uk/residual-stress-measurement/ultrasound and https://sonats-et.com/en/residual-stress/eddy-current-testing/

Table References: (Aleshin et al. 2016; Buddu et al. 2015; DebRoy et al. 2018; du Plessis et al. 2018b; Lopez et al. 2017; Lou et al. 2018; Lu and Wong 2017; NiPeijun 2000; Östlund and Berglund 2019; Sharratt 2015; Taheri et al. 2017; Thompson et al. 2016)

3.4 Other potential techniques

There are many less common NDE techniques that are either not widely used or are not approved by ASME Code for pre-service or in-service NPP examinations. A few that may be of interest are briefly outlined in Sections 3.4.1–3.4.4. Significant research has been conducted on each of these techniques, and they may be viable for in-plant use in the near future, depending on industry drivers. For example, full matrix capture (an advanced phased-array UT method) is being adopted into the 2019 edition of the Boiler Pressure and Vessel Code (BPVC).

3.4.1 Thermography

Overview: Thermography uses infrared (IR) radiation to detect surface and sub-surface cracks and density variations. Thermography relies on the notion that discontinuities heat up or cool down at different rates than the parent material; therefore, detectability depends on the contrast of thermal properties and heat flow.

Thermography is used extensively for in-process monitoring because it can monitor the temperature of the melt pool and thermal gradients without requiring contact with the component.

For post-process NDE, resolution can be poor (~10 cm [4 in.]), and it often requires an external heat source, such as an induction coil. For in-service NDE, it is rapid and can be used over large areas, but environmental conditions may prevent its use.

References: (Lopez et al. 2017; Mandache 2019; Sharratt 2015; Taheri et al. 2017)

3.4.2 Laser UT

Overview: Laser UT uses a laser pulse to induce a thermal shock and therefore a cascade of vibrational energy through the component, which can be detected using UT methods.

For in-process monitoring, a non-contact approach may be used if optical laser vibrometry is used for detection. However, this method often results in some ablation, which may make it undesirable for monitoring the AMT build process. To date, this process is not well studied for AMT.

For post-process and in-service NDE, this method can provide depth information with good resolution (~1 mm [0.04 in.]). Contoured surfaces are not a problem. However, rough surfaces may prevent conventional UT transducers from coupling well and may induce scatter if laser vibrometry is used.

References: (Cerniglia et al. 2015; Chauveau 2018; Choi and Jhang 2018; Davis et al. 2019; Everton et al. 2015; Lévesque et al. 2016; Volker et al. 2019)

3.4.3 Full matrix capture (FMC)

Overview: FMC is a UT data acquisition technique that uses a matrixed probe (i.e., a probe with a 2D matrix of transmitting and receiving elements). FMC emits energy from each individual element one at a time, while "listening" with all the other elements. With this approach, beam steering, sensitivity, and focus are improved over standard phased-array UT. This method, together with an analysis approach called total focusing method (TFM) allows for well-focused, full volumetric scanning with a single pass of a UT probe.

This method is not currently applicable to in-process monitoring because it requires contact and scanning with a UT probe.

For PSI and ISI, this method is currently gaining momentum in the NDE community. However, FMC has several downsides that need to be overcome. For example, FMC is slower than conventional UT, very large data files are generated for encoded FMC exams, a high level of computing power is needed to process the data, and larger probes are needed than for conventional UT.

Because FMC is an emerging method in NDE, there are very few published AMT studies to date with FMC. FMC is currently being adopted into the 2019 edition of ASME Code in Section V, Article 4, Mandatory Appendix XI with additional guidance in Nonmandatory Appendix F. It is anticipated that interest in FMC will increase.

References: (Chauveau 2018; Javadi et al. 2019; Mohseni et al. 2019; Xu et al. 2017)

3.4.4 Non-linear UT

Overview: Non-linear UT is an application of UT that typically uses higher amplitude and lower frequency sound waves to induce non-linear signal responses (i.e., distortions in the ultrasonic wave) from flaws.

This method is not well suited for in-process monitoring because it requires contact with a UT probe.

Non-linear UT is potentially very sensitive to cracks and pores, but it is still highly experimental. There are no approved uses in nuclear NDE and no proven applications for AMT.

References: (Koester et al. 2017; Prevorovsky et al. 2019)

4.0 Knowledge gap analysis of applying NDE to AMT nuclear components

4.1 Identified gaps in applying NDE to AMT nuclear components

In reviewing the literature, several reports and papers discussed knowledge gaps, challenges, and issues that exist in applying NDE to AMT components. Most of these references are focused on PBF techniques, partially because there are many references about PBF. For example, a Google Scholar search of *NDT “powder bed fusion”* returned 795 results, whereas a search of *NDT "powder metallurgy hot isostatic pressing"* returned 3 results and *NDT PM-HIP* returned 11 results.[1] Furthermore, because PBF is a relatively new technique, many NDT gaps exist —especially pertaining to nuclear applications. On the other hand, there are many references related to NDT of EBW, since EBW has been around for many decades. NDE methods and techniques used to examine EBW joints do not differ from those used on conventional welds, so relatively fewer NDE gaps specific to EBW were identified.

Because of the similarity of flaw types across AMT processes, the NDE gaps and applications were extrapolated across processes. Relevant knowledge and research gaps were identified and noted, and identical or similar gaps were grouped together. A priority score of High, Medium, or Low was assigned to each gap based on anticipated PSI and ISI needs and the importance for being able to apply pre-service and in-service NDE to AMT materials in nuclear power plants.[2] The priorities were *determined from an NDE perspective*. In other words, factors considered that facilitate reliable and repeatable inspections that can locate, identify, and characterize critical flaws. This perspective does not necessarily encompass component safety and reliability. PNNL subject matter experts relied on their combined experience in NDE research, in-service inspection, and ASME Boiler and Pressure Vessel Code to formulate the rankings. Table 4.1 lists the NDE gaps and the references where the gap was identified, where applicable. Items in the table are listed in order of priority and are numbered for convenience of referencing. It should be noted that the listed gap references come from a range of disciplines and not just NDE. Furthermore, most of the references cited in the table below are evaluations or studies conducted outside the nuclear industry. They are included here because many of the NDE gaps identified apply to AMT components in general. One reference in particular, the “Standardization Roadmap for Additive Manufacturing,” thoroughly describes and ranks many gaps for the AMT industry as a whole (including defense, medical, and aerospace), along with several NDE gaps; however, the nuclear industry was not a specific focus of that report (AMSC 2018).

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[1] Search conducted on 09 June 2020. Note that “NDT,” or “non-destructive testing” returns more search results than “NDE.” However, both terms were used.

[2] These gaps were ranked in priority as determined by experts in NDE and in-service inspection of nuclear components. The authors recognize that the NDE priority ranking may differ from the opinions of members of the AMT industry or regulators.

Table 4.1 NDE gaps for AMT nuclear components

No.	Identified NDE Gap	Gap References
1	**Validation of NDE techniques with destructive testing** Validation of NDE methods and techniques is absolutely required in order to evaluate the effectiveness and limitations of NDE. Destructive testing is the only guaranteed method of establishing the true-state of flaws and defects in mockups. Unfortunately, a mockup can only be destructively tested once, so validation of NDE is an expensive process. **Priority: High** Destructive testing will be necessary for validating NDE methods, particularly after critical flaw types, sizes, and locations have been identified. **Recommendation**: NDE validation studies should commence as soon as possible and be done in conjunction with destructive testing studies (e.g., determining critical flaw properties, assessing build quality) to save on costs.	(Sharratt 2015), (Lu and Wong 2018), (Mandache 2019)
2	**Will the grain structure of the components interfere with UT detection?** Grain structures in AMT components have been well-studied and are typically small but can be larger than grains in wrought stainless steel and approximately the same size as grains typically observed in austenitic welds. Grain structures in PBF components are typically anisotropic and tend to have longer dimensions in the build direction, although grain structures can be changed to more equiaxed by heat treatment (DebRoy et al. 2018). Grains resulting from PM-HIP tend to be small (~20–100 μm [8×10^{-4} – 4×10^{-3} in.]) and equiaxed, making such materials easier to inspect with UT (Dugdale and Borradaile 2013; Mashl 2015). Grains particularly inhibit UT because grains cause significant beam attenuation, scatter, and increased noise. This is a well-known and well-studied phenomenon when examining austenitic welds and CASS materials (Anderson et al. 2011; Crawford et al. 2009; Diaz et al. 2011; Jacob et al. 2019). If the noise introduced by the grains is of comparable intensity to the signal received from the flaws, then flaw detection will be challenging—especially when the flaws are small porosities. Knowing the grain structure can help inform the UT technique. For example, lower frequencies (longer wavelengths) penetrate through granular structures better but at the expense of resolution and may miss small cracks and pores. Also, longitudinal sound waves penetrate granular structures better than transverse waves. Furthermore, when grain sizes are approximately the same as the wavelength of sound, the sound is strongly scattered and attenuated. The grain sizes in AMT components may therefore limit the ultrasonic wave modes and frequencies that can penetrate and the size of flaws that can be detected. **Priority: High** Grain structures are a well-known confounding factor for volumetric UT examinations in materials such as austenitic welds. The sooner the deleterious effects of AMT grains on UT sound propagation are known, the sooner alternative methods can be developed and tested, if necessary. **Recommendation:** Research into the effects of AMT grain structures on	

No.	Identified NDE Gap	Gap References
	UT signal-to-noise, scattering, and attenuation should commence immediately on existing AMT specimens/mockups.	
3	**What is the relevant inspection volume?** Conventional NDE inspections focus on weld joints, since welds have been identified through research and experience as the regions with the highest probability of crack formation and failure. Based on information to date, some AMT components will be near-net shape and have no weld joints, and subassemblies may have a single circumferential weld to join them. Accordingly, conventional inspection volumes (i.e., the inner one-third of the component volume of the weld region for ISI) may not be the only relevant volume of concern for inspections. If pores are determined to be nucleation points for cracks and if pores are known to occur throughout the component volume, then does the entire component volume need to be inspected? If so, how often? Is it practical or possible to inspect the entire volume of a large component, keeping in mind that surface roughness has been identified as a significant inspection issue for AMT components? There are several options: inspect the entire volume, inspect a (to be determined) risk-informed or statistically-determined sub-volume, inspect random sub-volumes, or inspect none of the volume. **Priority: High** This is an important question that should be addressed before meaningful work on volumetric inspections of AMT components can begin. **Recommendation:** Additional effect-of-defect and crack growth-rate studies are needed before this gap can be thoroughly addressed. However, work on determining optimal volumetric inspection parameters and techniques should begin immediately.	
4	**Component surface finish** Surface finish was recognized by many authors as a significant challenge to the application of most NDE techniques to AMT components. In the nuclear industry, component surface condition has long been a critical factor with respect to achieving an effective and reliable examination of components. Two of the more common reasons for not achieving complete volumetric weld examination coverage have been the presence of weld crowns and irregular inspection surfaces. ASME Code Section XI, Nonmandatory Appendix D, for example, recommends no more than a 0.8 mm (1/32 in.) gap between any part of the search unit face and the examination surface. Surface finishing/contouring of certain piping surfaces/welds was required after plants had begun to operate to allow effective NDE to address emerging safety issues. Given that AMT component surface finish could be a significant challenge to effective and reliable NDE, empirical studies will be needed to establish the degree of surface roughness that facilitates inspectability. In one example, Yusa et al. (2016) used ET on artificial cracks made in a specimen manufactured with PBF, but prior to tests, the surface was polished to a roughness of Ra=0.04 µm. For comparison, PBF results in typical surface roughness of 5–30 µm, and a standard machined surface roughness is ~3 µm.[1] **Priority: High**	(Todorov et al. 2014), (Waller et al. 2014), (Mani et al. 2015), (Sharratt 2015) (Lopez et al. 2017), (Lu and Wong 2017), (Nilsson and Johansson 2017), (Taheri et al. 2017) (AMSC 2018), (Hassen and Kirka 2018), (Koester et al. 2018a), (Koester et al. 2018b), (Ahmed 2019), (Bishop-Moser 2019), (Buchanan and

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[1] Digital Alloys' Guide to Metal Additive Manufacturing – Part 11 https://www.digitalalloys.com/blog/surface-roughness/

No.	Identified NDE Gap	Gap References
	The ability to inspect components is directly affected by surface finish, which is therefore important for ensuring component integrity. The effects of surface finish on examination quality is widely recognized as a problem for NDE. Methods of finishing surfaces currently exist, but they would need to be mandated on AMT components. **Recommendation**: Empirical NDE studies and a cost/benefit analysis are needed to determine the level of surface roughness that is tolerable. Many requests for relief from the requirements to conduct NDE have been submitted to the NRC with respect to the current fleet of NPPs. Surface condition of AMT components will likely result in additional relief requests, so attention should be paid to this issue as early in the planning process as practicable.	Gardner 2019), (Mandache 2019)
5	**Inspection of large components and size limitations** Large NPP components, such as reactor pressure vessels, are currently inspected routinely, with the focus primarily on weld joints. However, with the relevant inspection volumes of AMT components identified as a significant gap (Gap #3 of this table), the ability to fully inspect large volumes requires consideration. AMT components for NPP reactor applications are expected to be much larger than components made in other industries that typically measure parts in centimeters or inches. CT, which is limited to small parts, was identified in many references as being the ideal method of inspecting AMT parts. However, upper and lower reactor head assemblies of SMRs are expected to have diameters of about 4 m (13 ft) and heights exceeding 20 m (66 ft) (Gandy 2019; Gandy and Stover 2018; Matthews et al. 2016). Only one reference was found in the preparation of this report describing NDE of large AMT components (Gandy 2015), making this a significant knowledge gap. Absent any breakthroughs in CT or other inspection technologies for large components, ASME Code Section III currently relies on RT and UT to ensure component weld integrity during fabrication. It will be important to closely monitor proposed inspection methods and prioritize and coordinate efforts across research groups in order to address this gap efficiently and effectively. **Priority: High** Scaled AMT mockups of SMRs currently exist, and plans for creating full-size components are being considered. The ability to examine large components is essential to nuclear NDE. **Recommendation**: Design empirical research or proof-of-concept studies to ascertain and solve the specific hurdles presented by large AMT components. Allow collaborative access to existing large-scale AMT mockups.	(Bond et al. 2014), (Babu et al. 2016), (Thompson et al. 2016), (Albakri et al. 2017), (Lu and Wong 2017), (Nilsson and Johansson 2017), (Seifi et al. 2017), (Taheri et al. 2017) (Hassen and Kirka 2018), (Koester et al. 2018a), (Koester et al. 2018b), (Bishop-Moser 2019), (Mandache 2019)
6	**Can the critical defects be detected with current NDE technology?** Once the critical defects are determined from effect-of-defect studies, the NDE detection limits are understood, and the inspection volume is determined, then the results of the findings need to be connected. Whether the critical defects can be detected effectively and reliably in large NPP components using current technology is an open question. Finding the answer to this question should result from a natural progression of research.	

No.	Identified NDE Gap	Gap References
	Priority: Medium The critical defects first need to be identified through materials testing. **Recommendation**: Research into flaw detection can commence using volumetric NDE and existing mockups or mockup designs. Destructive testing will be necessary until intentional flaws can be reliably and reproducibly included in the build process. The results then can be correlated to results of critical defect studies. Modeling and simulation may provide some answers on the anticipated sensitivity of UT to defects such as porosities.	
7	**Methods for examining complex geometries and/or internal geometries** NDE of complex geometries is a current problem with conventional construction. For example, it is difficult to couple a UT probe to a weld crown or a tight radius of curvature, thus making the inspection of certain weld joints difficult if not impossible. However, custom probe fittings can be created for many situations to allow coverage. This NDE gap may be compounded with AMT components, because there are few build restrictions to component complexity (design restrictions notwithstanding), particularly with PBF, but also with PM-HIP (Gandy 2015; Hjorth 2007). PBF components may even have intentional internal voids (e.g., to reduce weight) that will prevent the penetration of ultrasonic waves or access for VT, PT, MT, or ET. If complex geometries are used in NPP AMT components, particularly with new construction, then alternative NDE methods or techniques will have to be developed for volumetric inspections. Finalizing the design of AMT components without the harmonization of the design and inspection codes and the ability to ensure effective and reliable NDE will likely result in associated requests for relief. **Priority: Medium** AMT component geometries do not pose an immediate challenge to nuclear NDE, since component designs are not finalized. Pressure-bearing components are not expected to contain internal voids. However, certain component designs, such as nozzles and transitions to piping, should be considered a priority for NDE. **Recommendation**: NDE should be considered during the design phase so that uninspectable geometries can be avoided (changes would also be required to ASME Code Section III). Research into the use of conformable or adaptable UT wedges, or the use of alternative inspection techniques (e.g., surface waves, plane waves, etc.), may be needed.	(Bond et al. 2014), (Waller et al. 2014), (Sharratt 2015) (Albakri et al. 2017), (Koester et al. 2017), (AMSC 2018) (Brierley et al. 2018), (Colosimo et al. 2018), (Hassen and Kirka 2018), (Koester et al. 2018a), (Lu and Wong 2018), (Rebak and Lou 2018), (Bishop-Moser 2019), (Mandache 2019), (Simpson et al. 2019)
8	**Reference and defect mockups standards** Mockup standards are required for determining procedure qualification, personnel qualification, equipment calibration, and for confirmatory research. Part of this gap is addressed by the “*Standardize proprietary AMT processes and manufacturing methods”* gap in Section 4.1.1. A critical question is: can standard defects be reliably manufactured into mockups? For example, Yusa et al. (2016) generated artificial “cracks,” or notches, using a PBF technique and tested the detection capabilities of ET against the design true-state. They showed that the flaws were created with sub-millimeter precision, but the presence of unintentional flaws (porosities and LOF) was a problem. du Plessis et al. (2016) showed that the creation of small intentional defects can be difficult to control	(Waller et al. 2014), (Sharratt 2015) (Seifi et al. 2017), (AMSC 2018), (Koester et al. 2018a), (Lu and Wong 2018), (Moore et al. 2018), (Bishop-Moser 2019), (Mandache 2019),

No.	Identified NDE Gap	Gap References
	using PBF. Depending on directionality of the build, either unintended fusions occurred to close narrow defects or defects were larger than intended. Unexpected porosities were also found. Koester et al. (2017) used UT to attempt to detect intentional porosities placed using powder-bed AMT methods, but they observed that "Some uncertainty remains as to the actual shape and size of the defects and what, if any deviation from their specified shapes exist." Adding reference flaws, such as pores or cracks, to PM-HIP materials may be problematic if the PM-HIP process closes the flaws. **Priority: Medium** With no AMT components that require NDE currently in nuclear plants or planned for the near-term, there is no immediate need for NDE reference standards. However, as confirmatory NDE research ramps up with AMT components, reference standards will be necessary. **Recommendation**: Creating precise reference standards will be feasible after AMT build processes have become more standard and reliable and once more specific types of AMT NPP components and NDE methods are established. Research into controlled and repeatable creation of a variety of intentional defects using AMT methods should continue.	(Mayfield and Nichol 2019)
9	**Modeling and simulations** Modeling and simulation can be used in the build process to establish build parameters and predict residual stress, both of which may be critical to minimizing defects; this is not directly related to NDE. However, modeling and simulation in NDE can be used to predict SNRs, flaw response signals, probability of detection, and inspection parameters for ET, UT, and RT. In one reference, UT simulations were used to help predict POD in an EBW mockup (Dominguez et al. 2012). Models can be used to guide the design of, for example, flaw standard mockups and performance demonstration mockups. **Priority: Medium** There is no immediate need for modeling and simulation of NDE in AMT components; however, a modest modeling effort will help inform and guide NDE inspection approaches. For example, as effect-of-defect studies are carried out, modeling may help predict detectability prior to design and creation of reference and defect standards. If flaws are not predicted to be detectable, then alternative NDE methods may need to be developed. **Recommendation**: Modeling will be a useful tool in forming NDE approaches as more information is learned about the types, sizes, and geometries of AMT components and critical flaws. However, modeling cannot be used as a substitute for empirical or confirmatory NDE research.	(Bond et al. 2014), (Mani et al. 2015), (AM-Motion 2018), (Koester et al. 2018a), (Lu and Wong 2018), (Bishop-Moser 2019)
10	**Component qualification/acceptance standards** Component qualification methods and standards need to be established by the industry and regulators. NDE plays a critical role in determining whether components pass quality acceptance tests once the standards are developed. Note that this gap focuses on what standards will be used to qualify a component using NDE as opposed to how the build process may directly affect application of NDE.	(Aaltonen et al. 2009), (Kumar 2011), (Bond et al. 2014), (Babu et al. 2016), (Seifi et al. 2017), (AMSC 2018),

No.	Identified NDE Gap	Gap References
	Priority: Medium With no safety class 1 or 2 AMT components currently in nuclear plants or planned for the near-term, there is no immediate need for acceptance standards. However, the standards development process is long and arduous, so initiating the process soon will be beneficial. **Recommendation**: Current qualification and acceptance standards, and the NDE methods used to assure those standards, should be reviewed to determine applicability to AMT components. New standards should be adapted or created as necessary.	(Hassen and Kirka 2018), (Moore et al. 2018), (Buchanan and Gardner 2019), (Mandache 2019), (Mayfield and Nichol 2019)
11	**Automated inspection and interpretation** Routine inspections would benefit from automated data analysis, and this is an active area of research for many companies that provide ISI inspection software. With AMT components that may require inspection of their entire volume, automated data analysis, possibly based on AI or machine learning, will be a key for efficient examinations. For example, if certain porosities or LOF defects are common but are shown by effect-of-defect studies to be of no consequence, then automated analysis will be critical for allowing analysts to focus on the critical defects. Also, ever-decreasing numbers of qualified NDE experts in the nuclear industry may create a knowledge gap that automated data analysis can help fill, including for examinations of conventional components. Automated defect detection research is currently being pursued in many industries; cf. (Lee et al. 2019; Munir et al. 2018; Virkkunen and Koskinen 2019). **Priority: Medium** If entire volumes of AMT components will require inspection, then rapid data analysis techniques will be needed. Automated inspection and analysis is an emerging field of interest, even with current NDE inspections. With respect to AMT, it must first be determined whether or not entire volumes of large components need to be inspected, then it can be decided whether automated inspection and analysis are needed for AMT components in particular. Furthermore, inspections can continue to be done without automated methods. Therefore, this gap was ranked as medium priority. **Recommendation**: Current research in automated data analysis should be applied to AMT components and flaws. Machine learning or AI may be particularly useful for NDE of AMT components.	(Matthews et al. 2016), (Babu et al. 2018)
12	**SHM/lifetime monitoring** Long-term monitoring of AMT components can be implemented just as with conventional components. Typically, this involves attaching sensors to the surface of the component. The use of online monitoring/AE methods has been studied in the past by various organizations and, for example, was discussed as a means to lower operating inspection costs for pebble-bed reactors (Korsah et al. 2017). However, the research gap lies in the potential of using embedded sensors that are strategically placed during the build process. If permanently embedded sensors are to be used, they cannot be susceptible to heat or pressure damage during the build process, they must have an operational lifetime at least as long as that of the component, and they must not compromise the structural integrity of the component. It should be noted that a considerable amount	(Kumar 2011), (Sharratt 2015) (Fielding et al. 2016), (Albakri et al. 2017)

No.	Identified NDE Gap	Gap References
	of research has been conducted with respect to acoustic monitoring. **Priority: Medium** Until effect-of-defect and aging studies have been carried out to determine how AMT components will age or degrade while in service, SHM may be especially useful for long-term observation of AMT components so that crack formation can be detected and tracked. **Recommendation**: The initial focus should be on using standard SHM techniques for immediate implementation. Research can be done on developing state-of-the-art heat- and pressure-resistant embedded sensors as needs arise.	
13	**Inspection codes, standards, procedures, and protocols** Standards, procedures, and protocols currently exist for NDE inspections of conventional components, and it is expected that most of them can be readily adapted to AMT components. However, because of potential differences that exist in, for example, flaw types and locations, all of the codes, standards, procedures, and protocols that govern NDE inspections will have to be revisited and possibly revised. This gap will become a higher priority if the use of safety-critical AMT components in NPPs becomes more imminent. In the meantime, many other gaps must be addressed first, such as determining critical defect types and sizes, manufacture standardization, NDE technique validation, and understanding detection limits. **Priority: Low** With no safety class 1 or 2 AMT components that require NDE inspections currently in nuclear plants or planned for the near-term, there is no immediate need from an NDE perspective for inspection codes, procedures, or protocols. However, from a Code perspective, such codes, procedures, and protocols can take a long time to develop, so this gap should not be ignored. **Recommendation**: Current NDE inspection methods and standards should be reviewed to determine applicability to AMT components. Confirmatory empirical NDE studies will likely be needed.	(Waller et al. 2014), (Lopez et al. 2017), (AM-Motion 2018), (AMSC 2018), (Koester et al. 2018a), (Lu and Wong 2018), (du Plessis et al. 2019), (Mayfield and Nichol 2019)
14	**Inspection performance demonstration mockups** Mockups will have to be created for performance demonstration activities. Such mockups will have to be made using industry-standard techniques and will have to contain well-characterized flaws. Note that these mockups are different from reference and standard mockups, such as might be used to calibrate NDE equipment. **Priority: Low** Performance demonstration mockups will not be needed until inspection standards and mockup standards are established. **Recommendation**: Performance demonstration mockups can be designed and fabricated only after many of the other gaps have been addressed.	(Waller et al. 2014), (Seifi et al. 2017)
15	**Probability of detection (POD) data, methods, and standards** Once sufficient inspection data are available on critical flaws, it will be important to establish what the anticipated false positive and false	(Waller et al. 2014), (Sharratt 2015) (Bishop-Moser

No.	Identified NDE Gap	Gap References
	negative rates are and how such rates should be measured. This will first require a large number of well-characterized mockups with a variety of flaw types and locations to be manufactured. For example, some POD results on a small EBW mockup with hemispherical surface flaws have been published (Dominguez et al. 2012). **Priority: Low** This gap will require a large amount of data to be acquired on many AMT specimens, but only after other critical gaps have been addressed, such as determining critical flaw properties and standardizing build quality. **Recommendation**: Ongoing POD studies can be conducted as relevant AMT NDE data come available.	2019)
16	**Counterfeit parts detection** Counterfeit parts are a major problem in all industries and can adversely affect performance and safety (Leblanc and Abesamis 2016). Counterfeit parts could be introduced into the supply stream if measures are not taken to prevent it. Such parts pose unique safety challenges. NDE is currently used to help detect counterfeit parts or to identify genuine parts that are labeled in various ways, such as a void pattern or electronic signal. For example, Wei et al. (2018) show a method of using thermography or RT to read QR codes embedded during the PBF build process. **Priority: Low** Although it is likely that large nuclear components will be obtained through well-controlled sources, all components should be labeled with a method to verify authenticity. This gap may be more relevant to smaller, off-the-shelf components. **Recommendation**: AMT components can be designed to contain a label or tag that can be used to guarantee authenticity. Confirmatory research may be needed to demonstrate that such tags or labels can be read clearly and reliably using NDE.	(AMSC 2018)
17	**Can post-process NDE be scaled up to production environments?** Mass production requires effective detection methods. While mass production issues are not currently relevant to the nuclear industry, they may become important with the development of small modular reactors. In the meantime, detection methods may be required for the inspection of large components, or to meet production deadlines for multiple NPP units, for example. This raises several questions. If large-scale production of components or if production of very large components takes place, can NDE keep up with demand? Are NDE methods fast, cost-effective, and reliable enough? Are there enough qualified technicians? Can effective AI or automatic detection methods be used to make up for a shortage of technicians? As AMT components for nuclear applications become more common, these issues will likely be addressed on an as-needed basis. **Priority: Low** This is a question that may become relevant in the future as the use of AMT components in the nuclear industry becomes more common. **Recommendation**: Address NDE of AMT components throughput on an as-needed basis.	

4.1.1 Non-NDE gaps

In addition to the NDE gaps discussed above, several gaps were identified that will have direct bearing on some aspects of NDE but are not NDE knowledge gaps *per se*.

Non NDE Gap	Gap References
Descriptions of critical defect types, sizes, and locations This is a major gap for AMT components in general, particularly in new applications such as NPP. An understanding must be gained of which flaws originating from the build process are critical defects or have the potential to cause critical defects over time (a critical defect is a defect that may result in structural damage or failure). A common phrase in the literature to describe this issue is “effect-of-defect.” This gap represents a significant engineering and materials science research effort, but it must be completed before NDE can be effective at finding and identifying relevant flaws—NDE cannot identify critical defects if it is not known which defects are critical. Addressing this gap will also determine whether current NDE methods and techniques are adequate or if new techniques need to be developed. Once the critical defects are identified, research must be done to determine how such defects can be detected and discriminated from non-critical defects using NDE. For example, some studies suggest that certain porosities can be the initiation point for more significant cracking and failures; cf. Thompson et al. (2016). Porosities are a very common AMT defect, so if every porosity has to be identified with NDE, then it may affect the practicality of using AMT for large-scale components. **Priority: High** Without knowing the types, sizes, and potential locations of critical defects, NDE will not be informative. **Recommendation**: Significant research efforts should be made to determine the critical flaw types, sizes, and locations in nuclear AMT components. In addition, understanding relevant degradation mechanisms and flaw growth rates under operating conditions will need to be a focus of this research. NDE will likely not be involved until critical defect types are identified through destructive means.	(Waller et al. 2014), (Sharratt 2015), (Babu et al. 2016), (Seifi et al. 2017), (Chauveau 2018), (Kim and Moylan 2018), (Lu and Wong 2018), (Mandache 2019)
Standardize proprietary AMT processes and manufacturing methods This is not so much an NDE gap as it is an AMT industry issue. However, it directly affects the ability of NDE, which is highly standardized, to consistently and reliably detect flaws. Standardization of manufacturing processes must be accomplished prior to standardizing an NDE approach that is specific to a component or AMT method, so that the exact same NDE approach can be used repeatedly without recertification. In other words, an NDE inspection protocol should not be needed for each separate AMT manufacturer. Furthermore, AMT build standardization is critical to the creation of consistent defect standards, calibration standards, and performance demonstration standards. If two different companies produce nominally the same calibration standard but use different build parameters, what assurance is there that the products generate identical NDE responses? Research should be conducted to determine how reproducible the manufacturing standards are across AMT processes and even build-to-build on the same AMT equipment. Upwards of 50 build parameters can affect the quality of the final product in selective laser melting, a PBF	(Bond et al. 2014), (Town and Lawler 2015), (Babu et al. 2016), (Seifi et al. 2017), (Taheri et al. 2017) (AMSC 2018), (Hassen and Kirka 2018), (Koester et al. 2018a), (Buchanan and Gardner 2019), (Mayfield and Nichol 2019)

technique (Van Elsen 2007). These parameters include the scan speed, scan pattern, density of deposited energy, particle size, temperature gradients, and layer thickness. In addition, over 20 quality control operations should be performed in PM-HIP (Gandy et al. 2012). **Priority: High** Without standardization, build quality may vary unpredictably, and NDE inspections may have to be tailored to each specific build type. Also, inspection and reference standards cannot be made unless this gap is solved first. **Recommendation**: Although this is not an NDE gap *per se*, NDE should be used to assess build quality and help assure manufacturing standardization.	
What will be the NDE resolution requirements? This question cannot be adequately addressed without a better understanding of component material properties (grain structures), thicknesses, and the critical flaw sizes and locations. Once that information is known, NDE methods and techniques will have to be adapted or developed and subsequently demonstrated to provide the necessary resolution so that the critical flaws can be found with an acceptable probability of detection (which is yet to be determined). **Priority: Medium** The resolution requirements will depend on the results of critical defect studies and other high priority gaps. **Recommendation**: Although operating experience has shown that flaws will typically originate at the inside component surface, research into resolution limitations of volumetric NDE, especially UT, can begin using existing mockups. Modeling and simulation may provide some insight into resolution limitations.	
Residual stress measurements Residual stresses may cause part deformations and cracking during or after the PBF build process. Although recognized as a gap by some authors, measuring residual stress is probably not a necessary step for ISI. Residual stresses should be removed during post-build treatment, which is a concern for the build process, not the inspection process. Currently, weld residual stresses are relieved through mechanical or thermal means. NDE is often performed with UT before and after these processes (or during with AE) to detect any changes in the structural integrity of the part, but not to detect stresses directly. However, the long-term effects of AMT-related residual stress in nuclear components are not known. If residual stresses are not adequately addressed prior to component installation or are introduced during repair/replace activities, then it could potentially become an issue that is directly tied to component safety and will require in-service NDE. **Priority: Low** Residual stress measurement and mitigation should be considered part of the manufacturing process. However, methods of measuring residual stress with NDE may prove beneficial for long-term monitoring component integrity. **Recommendation**: Additional research is needed to determine the importance of residual stress in AMT nuclear components and how to effectively and reliably measure such stress, or its effects, using NDE.	(Babu et al. 2015) (Kim and Moylan 2018) (Koester et al. 2018a)

Inspection of green parts Green parts are those that have not yet received post-build treatment, such as heat treatment, sintering, or HIP. NDE of green parts may reveal critical flaws prior to finalizing the component. Some difficulty was reported in the literature in the inspection of green parts because of issues such as density gradients, surface roughness, and anisotropic sound velocity in UT inspections (James 2018; O'brien and James 1988). Since PSIs should be performed after all the build processes are complete, it is likely not necessary to inspect green parts unless the manufacturer deems it important as an intermediate step prior to finalizing the product. Such an inspection would not be classified as a PSI or ISI. **Priority: Low** Inspection of green parts should be considered part of the manufacturing process. Once a component is ready for installation, a PSI can be performed as usual. **Recommendation**: Research into NDE inspection of green parts may be informative to the build process, but it is not seen as necessary for PSI or ISI of nuclear components.	(O'brien and James 1988), (Bond et al. 2014), (James 2018)
Standard terminology for flaw identification Standard terminology has been established for the AMT industry in order to facilitate communication and regulation (ISO/ASTM 2015). This is recognized as an important step for the AMT industry. **Priority: Low** The NDE industry is quite mature and already has standardized terminology. **Recommendation**: The NDE community can adapt to terminology standardization made by the AMT industry. Coordination with the appropriate standards organizations will be required to standardize terminology across the industry and update the applicable codes and standards.	(AMSC 2018) (ISO/ASTM 2015)

4.1.2 NDE of Cold Spray

Nozzle clogging and poor surface preparation are the primary flaw mechanisms in material deposited by cold spray. Nozzle clogging reduces particle velocity, resulting in reduced mechanical properties and increased porosity. Poor surface preparation results in poor adhesion, or bonding, to the substrate. Causes of flaws include improper: powder preparation, powder handling, and path planning. The four primary NDE methods used to examine CS deposition are VT, PT, UT, and ET (Glass et al. 2018). Cold spray is a young technology, so there are relatively few references and studies describing the effectiveness of NDE techniques for evaluating CS depositions in the nuclear industry. In one report, the IAEA studied UT and ET for the inspection of copper coatings on used fuel cannisters (Liyanage et al. 2016). There are also some review articles that discuss the use of CS in the nuclear industry (c.f., (Champagne and Helfritch 2014; Pathak and Saha 2017; Yeom and Sridharan 2020)).

VT, including enhanced VT, can be used to examine the CS surface for imperfections such as chipping, cracking, and flaking. PT can also be used, but surface roughness or porosities may obscure cracks or other imperfections. Either method can be used to examine the visible regions where the CS deposit meets the substrate to look for indications of lack of adhesion, but this is limited to the periphery of the deposition.

UT is the most promising technology for detecting porosities, coating thickness, cracking, and lack of adhesion. Relatively high UT frequencies (>5 MHz) can be used because of the lack of attenuating grain structures. At 5 MHz, the wavelength would be about 1 mm and would therefore be appropriate for interrogating coatings that are about 1 mm thick; however, this assumption should be verified experimentally. Cracks and lack of adhesion can be measured using established UT methods because the echo signals from such flaws are well understood. Also, where an echo at the interface of the CS layer and the substrate can be identified, coating thickness can be directly measured (Glass et al. 2018; Singh and Singh 2020). Porosities can be measured directly, and small variations in porosity are easily detectable using UT. Currently, UT methods of examining CS materials are still in the experimental stages (Glass et al. 2018). Surface roughness may hinder the ability to inspect CS surfaces with UT. Laser UT, a non-contact UT technique, has been studied for examination of CS coatings (Levesque et al. 2019).

ET can be used to examine the CS layer for cracks, porosities, or inclusions if the layer is thin enough (Lareau et al. 2019). For example, in one study, the integrity of the bonding interface was examined on thin steel plates (Mi et al. 2007). Thin CS layers, <1 mm, may be used to mitigate chloride-induced stress corrosion cracking in fuel storage casks (Yeom and Sridharan 2020), implying that ET may be well suited for inspection of such layers. As with UT, surface roughness may affect the ability to inspect CS depositions. It is anticipated that ET is appropriate for coatings several millimeters thick, however additional work should be done to verify effective thickness limits.

4.1.2.1 Cold Spray Inspection Gaps

There are several knowledge gaps with NDE of cold spray materials.

- **Porosity:** Porosities in CS materials are similar to those in other AMT materials, and they present similar issues to NDE. Direct measurement of porosity density, location, and size is feasible using UT or ET. Because this is time consuming and labor intensive, automation would be ideal for scanning components that have large sections that have been coated with CS. One potential PSI approach could be to use the application robot for UT or ET inspection of components directly after spraying. For ISI, other automated approaches would need to be developed.
- **Coating/substrate adhesion:** Nondestructive measurement of the quality of coating/substrate adhesion is a recognized and difficult NDE problem that will likely be a long-term issue. Lack of adhesion may be partial or very localized and therefore difficult to detect. Porosities also result in signal scatter, which can hamper efforts to detect small signals from poor adhesion. A 2020 funding opportunity was released by the US Department of Defense to invite innovative solutions for this issue.[1]
- **Through-coating inspectability:** UT and ET can penetrate CS coatings and inspect the underlying material. Thick coatings may present problems for inspection, particularly if the coatings contain porosities. Understanding the various NDE capabilities in this context will require further research.
- **Thick cold spray builds:** Thick cold spray builds may present problems for inspection, particularly if the deposited material contains significant porosities. Understanding the depth limitations for UT and investigating iterative NDE during part build are important undertakings for enable cold spray additive manufacturing of nuclear components.

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[1] DoD. 2020. "Non-Destructive Evaluation of Bonded Interface of Cold Spray Additive Repair." Department of Defense.

- **Foundational Research and Guiding Documents:** Information in the literature for NDE of cold sprayed material is limited to small effort showing a specific application can be inspected. Published studies that investigate NDE of cold spray are needed to establish a technical foundation and best practices for inspection of cold spray additive manufacturing.

4.2 Gaps in current codes and standards

The ASME Code has not yet adopted standards regarding AMT, and current Code development is still in its infancy. To date, Section III Division 1 has adopted one related Code Case (in 2013 for PM-HIP of 316L stainless steel).[1] However, committees are actively considering the development of Code rules to address emerging issues related to AMT construction and testing. Other organizations, such as ASTM[2] and AMSC[3] (the America Makes & ANSI Additive Manufacturing Standardization Collaborative), are also engaged in developing and setting AMT standards.

ASME's Board on Pressure Technology Codes and Standards (BPTCS) and Board on Nuclear Codes and Standards (BNCS) has convened a Special Committee on Use of Additive Manufacturing for Pressure Retaining Equipment.[4] This committee is scheduled to meet quarterly during ASME's Boiler Code Week and has the following charter: "To develop a technical baseline to support development of a proposed BPTCS standard or guideline addressing the pressure integrity governing the construction of pressure retaining equipment by additive manufacturing processes. Construction, as used in this Charter, is limited to materials, design, fabrication, examination, inspection, testing, and quality control." From the February 5, 2020 minutes of the Special Committee:[5] "BPV Code Cases using additive manufacturing are being developed in conjunction with the BPV construction Codes. In the short term, direction developed by this Special Committee will guide the development and processing of these Code Cases." In addition, the Committee is currently working on a guideline document on standards development for PBF equipment with a target completion date of late 2020.

For several months, EPRI (under DOE project DE-NE0008521), along with several industrial partners, has been developing a technical "data package," or a technical basis document, for 316L Stainless Steel Manufactured via Laser Powder Bed-AM on additively manufactured stainless steel parts. The data package was recently presented to the BPTCS/BNCS Special Committee and is under consideration to support a Code case by the Section III Subgroup on Materials, Fabrication and Examination. The data package is specifically focused on the manufacture of 316L stainless steel components using laser powder bed additive manufacturing (LPB-AM). The components produced under the project via LPB-AM include pipe flanges, pipe tee sections, and valve bodies. The data package includes component builds from Westinghouse, Rolls Royce, Oak Ridge National Laboratory, Auburn University, and Oerlikon, along with supporting mechanical, microstructural, build property, and ultrasonic data.

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[1] ASME Code Case N-834, "ASTM A988/A988M-11 UNS S31603, Subsection NB, Class 1 Components."

[2] https://www.astm.org/Standards/additive-manufacturing-technology-standards.html

[3] https://www.ansi.org/standards_activities/standards_boards_panels/amsc/America-Makes-and-ANSI-AMSC-Overview

[4] Information on this committee is available at: https://cstools.asme.org/csconnect/CommitteePages.cfm?Committee=101029283

[5] Minutes of the Tenth Meeting of the BPTCS/BNCS Special Committee on Use of Additive Manufacturing for Pressure Retaining Equipment, Wednesday, February 5, 2020. Not publicly available.

Westinghouse and EPRI are expected to submit the data package to ASME Code, Section III. Information about the components that have been produced is available (Gandy 2018).

Aside from the ASME BPTCS/BNCS Special Committee's consideration of the EPRI Data Package, only two ASME Task Groups (TG) are currently working AMT: the TG on Additive Manufacturing for Valves and the TG on Division 5 AM Components.

ASME activities outside the realm of nuclear power involve the development of a national standard related to advanced manufacturing. ASME's Y14 Standards Committee established the Y14.46 subcommittee in support of the development of a new standard on AM..[1] It's charter, approved in October 2014, is to "Develop and standardize systems and indications to promote uniform product definition practices for AM. Create a broadly accepted standard that incorporates, expands, or refines international practices and symbology to enable AM product definition data sets to be created, interpreted, and consumed on a global basis. This standard shall ensure that component parts and component assemblies, produced from such AM product definition data sets, are subject to a single interpretation of engineering specifications and requirements for the purpose of conformance verification. This standard shall supplement the requirements of the Y14 series." In 2017, the subcommittee published a Draft Standard for Trial Use on AM (ASME 2017). The standard encompasses "engineering product definition and related documentation practices." The subcommittee's work is ongoing.

Currently, the only ASME Code activity occurring related to NDE is within ASME Section V and is regarding CT, although no requirements or guidelines have yet been established. Prior to adapting an NDE method to any component, the type of conditions or flaws expected to be present must be identified, and only after this can an NDE method/technique and personnel qualification criteria be established.

Table 4.2 lists the primary NDE-related AMT gaps with respect to the ASME Code and the references where the gaps were identified. A priority score of High, Medium, or Low was assigned to each based on the urgency for filling the gap from an NDE PSI or ISI perspective.

Table 4.2 AMT NDE gaps related to ASME code

No.	ASME Code Gap	References[1]
1	**Identification of Expected Flaws & Characteristics** Planar and laminar flaw conditions currently identified in the ASME Code are based on conventional manufacturing processes. Flaws that could inheritably occur during the AMT processes must be compared to conditions currently identified in ASME Section III, such as porosities, cracks, and LOF, to determine if the existing Code adequately addresses such conditions. Likewise, ASME Section XI must be evaluated with respect to flaws that might occur in AMT materials, and the in-service conditions currently addressed that are caused by fatigue, stress, or corrosion degradation. Residual stresses and interaction with fabrication defects have historically been proven to cause service induced flaws. These conditions should be assessed by proven criteria currently used to evaluate the most effective NDE approach and related personnel qualification requirements to ensure safety and quality.	ASME Section III NB-5000, NC-5000 ASME Section XI, IWB and IWC

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[1] Information on this subcommittee can be found at: https://cstools.asme.org/csconnect/CommitteePages.cfm?Committee=100749850

No.	ASME Code Gap	References[1]
	Priority: High Acceptance standards based on engineering analysis cannot be established until the types of flaws expected in the manufacturing process are identified. **Recommendation**: Identify and cross reference AMT flaw types with ASME Section III & Section XI flaw types.	
2	**Acceptance Standards** Defect acceptance standards currently identified in the applicable ASME Code section are well established; however, these cannot be applied to AMT processes without evaluating the impact of structural integrity. **Priority: High** The quality assurance and structural integrity of a component is based on acceptance standards applied to any manufacturing process conditions. Process qualification, process control, and performance demonstration have not yet been completed for any AMT process. Once the ASME Code establishes requirements for AMT, those requirements will drive applicable NDE requirements. The gaps outlined in this table are established for current fabrication processes; however, no data exists to validate these current requirements as applicable to AMT processes. **Recommendation:** Conduct an engineering analysis of component in-service stresses in relation to void conditions that could cause an in-service flaw.	ASME Section III NB-5000, NC-5000 ASME Section XI IWB, IWC
3	**Determination of Applicable NDE Methods** Well established NDE methods for visual, surface, and volumetric examination have evolved and been proven over time with conventional manufacturing processes. With new AMT processes, these methods cannot be assumed applicable until verified through testing with known flawed specimens. **Priority: High** Once flaw types and acceptance standards are developed, NDE methods that accurately detect and dimension these flaws must be experimentally verified. **Recommendation**: Conduct a research study with widely applied and accepted NDE methods on flawed AMT specimens that have surface and volumetric conditions.	ASME Section III NB-5000, NC-5000 ASME Section XI IWB, IWC
4	**Procedure Qualification** Procedures that define NDE examination requirements for conventional manufacturing processes are required to be demonstrated to the inspector, utility owner, or both based on requirements of the applicable ASME Code. No procedures have been qualified for the examination of AMT components. **Priority: Low** Examination procedures can be easily revised to include any specific AMT criteria or techniques. **Recommendation**: Prior to PSI and ISI of AMT components, procedures must be developed, demonstrated, and approved for to use.	ASME Section III NB-5000, NC-5000 ASME Section XI, IWA, Appendix I, Appendix III & Appendix VIII
5	**Personnel Qualification** The qualification of NDE personnel is well established and has been closely scrutinized for over 75 years. Current Code requirements for ASME Section III examination personnel are in accordance with the ASNT Recommended Practice SNT-TC-1A[2] that outlines training, experience, and testing	ASME Section III NB-5000, NC-5000

No.	ASME Code Gap	References[1]
	requirements to be certified (USNRC 2012a). The NDE techniques that may be applied to AMT components may be of a specialized nature and require training beyond currently established criteria. **Priority: Low** Training curriculum can be easily adapted from existing outlines. **Recommendation**: Training and testing criteria should be established for any specialized NDE techniques identified as applicable to AMT components.	ASME Section XI, IWA, Appendix VI and Appendix VII
	[1]The ASME Boiler and Pressure Vessel Code is not publicly available but can be obtained from ASME https://www.asme.org/codes-standards/find-codes-standards/bpvc-complete-code-boiler-pressure-vessel-code-complete-set [2]Can be obtained from https://www.asnt.org/MajorSiteSections/Standards/ASNT_Standards/SNT-TC-1A.aspx	

4.3 Summary

The following list combines all the NDE and Code gaps that were identified above as High, Medium, or Low priority from an NDE perspective. These were ranked from high priority to low priority within each level *based on current and anticipated PSI and ISI needs*. Many of these gaps are not solely related to NDE; they will require coordination and cooperation with other disciplines, such as AMT professionals, material scientists, design engineers, ASME Code experts, and regulators. As such, addressing the gaps will require collaboration across disciplines and potential reprioritization of the gaps based on current and anticipated NPP industry needs.

High Priority:

1. Identification of expected flaws and characteristics (Table 4.2 No.1)
2. Defect acceptance standards (Table 4.2 No. 2)
3. Determination of applicable NDE methods (Table 4.2 No. 3)
4. Validation of NDE techniques with destructive testing (Table 4.1 No. 1)
5. Determination of effects of AMT grain structures on UT (Table 4.1 No. 2)
6. Definitions of the relevant inspection volume (Table 4.1 No. 3)
7. Required level of component surface finish (Table 4.1 No. 4)
8. Size limitations for inspection of large components (Table 4.1 No. 5)

Medium Priority:

1. Effectiveness of defect detection with current technology (Table 4.1 No. 6)
2. Methods for examining complex geometries and/or internal geometries (Table 4.1 No. 7)
3. Reference and defect mockups standards (Table 4.1 No. 8)
4. Modeling and simulations to help inform volumetric NDE (Table 4.1 No. 9)
5. Component qualification/acceptance standards (Table 4.1 No. 10)

6. Automated inspection and interpretation (Table 4.1 No. 11)
7. Structural health monitoring/lifetime monitoring (Table 4.1 No. 12)

Low Priority:

1. Inspection codes, standards, procedures, and protocols (Note: this overlaps with ASME Code gap “Procedure qualification”) (Table 4.1 No. 13 and Table 4.2 No. 4)
2. Inspection performance demonstration mockups (Table 4.1 No. 14)
3. Personnel qualification (Table 4.2 No. 5)
4. POD data, methods, and standards (Table 4.1 No. 15)
5. Counterfeit parts detection (Table 4.1 No. 16)
6. NDE in production environments (Section 4.1. No. 17)

5.0 Conclusions

NDE methods and techniques have been used for decades to help assure the continued operational safety of the NPP fleet. There is growing interest in using advanced manufacturing techniques, such as PBF, DED, EBW, and PM-HIP, to create safety-critical and safety-significant components, such as those that may be pressure retaining. In addition, there is strong interest in using CS as a repair option. Thus, the effectiveness of applying existing NDE techniques to the pre-service and in-service safety evaluation of such components made or repaired with AMT processes must be carefully verified. From reviewing the literature in preparation of this report, 21 significant knowledge gaps that are relevant to NDE of AMT components and the related ASME inspection code were identified and ranked. Recommendations for how to address the gaps were also provided. In addition, CS inspection gaps were addressed. It should be remembered PBF and DED are relatively new AMTs, so most of the knowledge gaps arose in the context of those technologies. PM-HIP and EBW are relatively mature technologies, so establishing inspectability of such components may require less time and fewer studies.

Fully resolving the NDE gaps will take years of effort and cooperation between the nuclear industry, regulators, and independent research organizations. To facilitate progress and reduce costs, participants should freely share mockups, new NDE techniques, and lessons learned. Cooperation will also help the industry maintain maximum operational and public safety. Research efforts will likely be ongoing as new AMT methods and applications are developed. NDE and AMT research should continue in parallel to assure the inspectability of new safety-critical components.

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