Draft Guidelines Document for Additive Manufacturing—Laser Directed Energy Deposition

1. Introduction and Purpose

When finalized, this draft guidelines document (DGD) will provide U.S. Nuclear Regulatory Commission (NRC) staff with guidelines for conducting reviews of submittals that include components manufactured using additive manufacturing—laser directed energy deposition (L-DED). These guidelines are based on the NRC assessment of the impact on component performance of the identified differences between L-DED and traditional manufacturing methods as documented in "NRC Technical Assessment of Additive Manufacturing—Laser Directed Energy Deposition," (Agencywide Documents Access and Management System (ADAMS) Accession No. ML21292A188) (hereafter, "NRC technical assessment"), which builds on the Oak Ridge National Laboratory's (ORNL's) technical information and gap analysis, "Review of Advanced Manufacturing Techniques and Qualification Processes for Light Water Reactors—Laser Directed Energy Deposition Additive Manufacturing," (ADAMS Accession No. ML21292A187). This document provides L-DED-specific draft guidelines under Subtask 2C, "Action Plan for Advanced Manufacturing Technologies (AMTs)," Revision 1, dated June 23, 2020 (ADAMS Accession No. ML19333B973), as a supplement to the AMT generic draft guidelines document, "Draft AMT Review Guidelines" (ADAMS Accession No. ML21074A037) (hereafter, "draft generic guidelines").

When reviewing an AMT submittal, the NRC staff can refer to the generic guidelines, once finalized, which can assist the NRC staff's review of a submittal requesting the use of an AMT. The finalized generic guidelines along with this DGD will identify the generic and L-DED-specific information that could be necessary in a submittal in order to provide a timely and efficient review. The NRC technical assessment is also available for additional background and technical information to support the review of a submittal.

2. Brief Description of the NRC Technical Assessment of Laser Directed Energy Deposition

This section describes the purpose of the NRC technical assessment of L-DED, which provides the technical basis for the technical review guidelines described in this DGD. The primary objective of the NRC technical assessment is to describe the differences between an L-DED-fabricated component and a traditionally manufactured component, assess the impact that the identified difference has on component performance, and identify relevant technical information pertaining to these differences for L-DED-fabricated components. This DGD is intended to build on the NRC technical assessment and provide guidelines, when finalized, to the NRC staff by identifying important considerations when reviewing a submittal requesting the use of L-DED.

The overall impact to plant safety (e.g., safety significance) is a function of component performance and the specific component application (e.g., its intended safety function). These reports do not address the impact on plant safety, as such an assessment would not be possible without considering a specific component application. In addition to the technical review guidelines in this document, the NRC staff should consider the specific component application and the potential for secondary consequences, such as debris generation and associated impacts, when assessing the impact to overall plant safety.

As discussed in the NRC technical assessment, the NRC staff identified differences between AMT and traditional manufacturing processes by reviewing the information and gap analysis rankings from the ORNL report, as well as other relevant technical information (e.g., NRC regulatory and research experience, technical meetings and conferences, codes and standards activities, Electric Power Research Institute and U.S. Department of Energy products and activities).

3. NRC Generic Guidelines for Advanced Manufacturing Technologies and Laser Directed Energy Deposition -Specific Guidelines

The finalized generic guidelines will identify the information that could be necessary in a submittal to ensure a timely and efficient review. Appendix A to the generic guidelines identifies the five primary topics to be addressed in a submittal:

(1) Quality Assurance (QA): process followed during the manufacture and implementation of AMTs to ensure adherence to QA requirements (e.g., Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, “Domestic licensing of production and utilization facilities,” Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants”), established methods (e.g., commercial -grade dedication), or both

(2) Process Qualification: steps taken to demonstrate that the component will be produced with characteristics that will meet the intended design requirements

(3) Supplemental Testing: testing conducted to demonstrate that those material and component properties required to meet the design requirements are acceptable in the applicable service environmental conditions, and thus the performance of the component in service will be acceptable

(4) Production Process Control and Verification: steps taken to ensure that each component will be produced in accordance with the qualified process and, if the production process fails to meet the qualification essential variables, the steps taken to reestablish the qualified process

(5) Performance Monitoring: actions taken to provide assurance that the component will continue to meet its design requirements until the end of its intended service life

Table 1 includes the identified differences between L-DED and traditional manufacturing outlined in the NRC technical assessment (both generic and 316L material-specific) and identifies those primary elements from Appendix A to the generic guidelines that are expected to be most commonly applicable to each of the differences. However, the applicable primary elements may vary on a case-by-case basis, depending on the licensee’s approach to demonstrating quality and safety. Therefore, this table provides an example of applicable elements and reflects that not every element in Appendix A to the generic guidelines is applicable to every difference listed in Table 1.

QA comprises all those planned and systematic actions necessary to provide adequate confidence that a system or component will perform satisfactorily in service. QA processes implemented during the manufacture and implementation of AMTs ensure that QA requirements (e.g., 10 CFR Part 50, Appendix B), established methods (e.g., commercial-grade dedication), or both, have been satisfied. For AMTs, a QA program will specifically address novel or unique aspects of manufacturing or implementation specific to the AMT. Therefore, Table 1 does not explicitly include QA as a distinct column, but QA is applicable to each of the differences between traditional manufacturing and L-DED processes identified in the table and achieved through successful performance of the other four Appendix A items: process qualification, supplemental testing, production process control and verification, and performance monitoring.

Tables 2A and 2B provide the technical review guidelines. Table 2A lists the generic differences between traditional manufacturing and L-DED. Table 2B lists the material-specific differences between traditional manufacturing and L-DED 316L stainless steel. 316L is the alloy relevant to L-DED-fabricated nuclear applications with the most information currently available in the open literature. While Table 2B is also based on the available information in the open literature for 316L, the differences identified in Table 2B involving material-specific properties and performance would need to be considered for any newly fabricated material using L-DED. In general, material-specific data for the proposed processing and post-processing parameters are important for any nuclear L-DED-fabricated component to ensure adequate component performance in the applicable environment, including properties (e.g., fracture toughness, tensile strength) and resistance to aging mechanisms (e.g., thermal aging, irradiation effects, and stress corrosion cracking (SCC)). It is important to note that the feedstock (i.e., powder vs. wire) may impact the differences listed in the tables. The impact that feedstock selection has on a specific difference is noted as appropriate in Tables 2A and 2B.

Tables 2A and 2B provide technical review guidelines related to the differences for the L-DED process and component performance through the following columns:

- Difference: identifies the differences between L-DED and traditional manufacturing outlined in the NRC technical assessment
- Key Technical Information: summarizes the key technical information documented in the NRC technical assessment for easy reference
- Technical Review Guidelines: provides additional guidelines related to the differences between L-DED and traditional manufacturing that the staff should consider when evaluating how a licensee's or applicant's submittal addresses the differences between L-DED and traditional manufacturing

It is important to note that a given submittal need not include all elements of these tables.

Table 1. Relevant Elements from Appendix A to the Generic Guidelines

Difference	Process Qualification	Supplemental Testing	Production Process Control and Verification	Performance Monitoring
L-DED Machine Process Control	X		X	
Powder Feedstock Quality	X		X	
Wire Feedstock Quality	X		X	
L-DED Build Process Management and Control	X		X	
Witness Specimens	X		X	
Thermal Post-Processing	X		X	
Local Geometry Impacts on Component Properties and Performance	X	X		
Heterogeneity and Anisotropy in Properties	X	X		
Residual Stress	X	X		
Porosity	X	X		
Surface Finish	X	X	X	
Tensile Properties	X	X		
Initial Fracture Toughness	X	X		
Thermal Aging		X		X
SCC and Corrosion Resistance		X		X
Fatigue		X		X
Irradiation Effects		X		X
High Temperature Time-Dependent Aging Effects (e.g., Creep and Creep-Fatigue)		X		X
Weld Integrity		X		X
Weldability / Joining	X		X	

Table 2A. Technical Information and Review Guidelines—L-DED Generic

Difference	Key Technical Information	Technical Review Guidelines

L-DED Machine Process Control	• Control of L-DED files is needed to ensure process control. Improper file control can significantly impact final component properties and performance and affect fabrication replication. Cybersecurity, database traceability, managing software updates, and similar items are highly important to ensuring end-use component quality.
	• Machine calibration is vital for fabrication replication, particularly ensuring correct feedstock deposition parameters, laser power, laser spot size, travel speed, and atmospheric quality control in addition to geometric tolerances. For LP-DED, this includes contamination minimization if recycling powder.
		Process Qualification
		• The applicant should identify the essential variables related to L-DED machine process control and demonstrate that controlling these variables within identified ranges will ensure reliable, adequate, and repeatable component properties and performance.
		• At a minimum, the process qualification should consider the following essential variables:
		  ○ software file preparation (e.g., L-DED software version, and L-DED software settings)
		  ○ calibration of L-DED machine and subsystems (e.g., build stage, feedstock deposition, laser optics, atmosphere control)
		• The applicant should identify additional specific essential variables and their ranges as appropriate.

		Production Process Control and Verification • During production, the applicant should demonstrate that process control and verification will maintain the production process within the qualified essential variable ranges. • The applicant can use a variety of machine process controls approaches to demonstrate process control and verification, including, but not limited to periodic machine calibration verification.

Powder Feedstock Quality	• Detailed powder characterization and control, preventing powder contamination, and maintenance of an inert gas environment are important factors in ensuring powder quality and reducing powder variability.
	• Powder contamination is a critical issue that may adversely affect material properties and process by introducing oxides and changing chemical composition.
	• Thorough cleanliness activities, dedication of LP-DED machines to specific alloys, and periodic replacement of feedstock conveying tubes and components
		Process Qualification
		• Through process qualification, the applicant should provide sufficient data to identify the essential variables related to powder quality and demonstrate that controlling these variables within identified ranges will ensure reliable and adequate component properties and performance.
		• At a minimum, the process qualification should consider the following essential variables for powder quality:
		  ○ chemical composition, including trace elements
		  ○ powder size and morphology distribution
		  ○ powder flowability
		  ○ acceptance criteria or limits for powder reuse
		• The applicant should identify additional specific essential variables and their ranges as appropriate.

		Production Process Control and Verification • During production, the applicant should demonstrate that process control and verification will maintain the production process within the qualified essential variable ranges.

Difference	Key Technical Information	Technical Review Guidelines

	can be conducted to address powder contamination.
	• LP-DED can achieve high powder utilization exceeding 90% in some cases, which makes powder reuse less essential than in LPBF.
	• Powder reuse can provide substantial cost benefits but can introduce significant variability in powder composition. Powder characterization and associated acceptance criteria may be warranted to reuse powder, especially for safety significant components.
		• The applicant can use a variety of powder quality approaches to demonstrate process control and verification, including, but not limited to, the following:
		  ○ testing final components on a sampling basis
		  ○ characterizing essential variables by routine powder sampling before initial use and reuse
		  ○ implementing procedures to minimize powder contamination during production

Wire Feedstock Quality	• Welding wire feedstock is almost always used for LW-DED applications that is certified by the manufacturer to conform to AWS or ISO standards for the specific alloy and wire product in question.
	• There is a long-established history of ensuring welding consumables conform to applicable standards for industrial welding applications.
	• Wire chemistry and processing-path must be tightly controlled.
	• Contamination concerns are well understood and are less of a concern as compared to powder feedstock.
		Process Qualification
		• Through process qualification, the applicant should provide sufficient data to identify the essential variables related to wire feedstock quality and demonstrate that controlling these variables within identified ranges will ensure reliable and adequate component properties and performance.
		• At a minimum, the process qualification should consider the following essential variables for wire feedstock quality:
		  ○ chemical composition
		  ○ material homogeneity
		  ○ surface condition, e.g., roughness
		  ○ size
		• The applicant should identify additional specific essential variables and their ranges as appropriate.
		Production Process Control and Verification
		• During production, the applicant should demonstrate that process control and verification will maintain the production process within the qualified essential variable ranges.
		• The applicant can use a variety of wire feedstock quality approaches to demonstrate process control and verification, including, but not limited to testing final components on a sampling basis.

Difference	Key Technical Information	Technical Review Guidelines

L-DED Build Process Management and Control	• Build interruptions (planned and unplanned) can have a very significant impact on quality of the component and should be avoided.
	• In situ monitoring without feedback control can be used to identify issues in the build process in real time and may be used in conjunction with other approaches to demonstrate process control.
	• In situ monitoring with feedback control is still a developing area of research and should be carefully managed and strongly demonstrated if proposed for use during production.
	• Management, storage, retrieval, and analysis of the data generated during the L-DED process is critical for accelerating process optimization, although proper identification, handling, and evaluation of this information is still under development.
		Process Qualification
		• The applicant should identify the essential variables related to L-DED build process management and control and demonstrate that controlling these variables will ensure reliable, adequate, and repeatable component properties and performance.
		• At a minimum, the process qualification should consider defining essential variables with demonstration for the following:
		  ○ build interruption (e.g., duration, frequency, component location, and geometry)
		  ○ loss of environmental control (e.g., event time, degree of air ingress).
		• The applicant should identify additional specific essential variables as appropriate.
		Production Process Control and Verification
		• The applicant should demonstrate that process control and verification will maintain the production process within the qualified essential variable ranges.
		• The applicant can use a variety of approaches to demonstrate process control and verification, including, but not limited to, the following:
		  ○ monitoring build issues (e.g., incomplete spreading, delamination, or other events that may result in component rejection)
		  ○ confirming build parameters, such as chemical composition and contamination (e.g., oxides)
		  ○ for location-specific measurements, measuring of materials properties (e.g., strength, hardness), appropriately demonstrating how they are representative of geometry, size, location, and spatial orientation
		  ○ confirming of expected material microstructure and characteristics (e.g., residual stress, porosity, surface finish)
		  ○ scrapping any builds that deviate from the qualified essential variable ranges.
		• Due to the lack of maturity of the approach, in situ monitoring with feedback control should be adequately supported with a strong basis on the effectiveness of the approach.

Witness Specimens	• The most highly representative test specimens are obtained from end-use component geometries.
	  ○ Geometry impacts, particularly thickness, on witness specimen microstructure and properties should be considered and addressed.
	• Optimal witness specimen parameters (geometry, size,
		Process Qualification
		• The applicant should identify the component properties and characteristics for which witness testing will be used to demonstrate process qualification.
		  ○ Component properties and characteristics for which witness testing could be used include various microstructure and material properties (e.g., composition, density, hardness, microstructure, tensile, fatigue, fracture toughness, corrosion testing).
		• The applicant should demonstrate that witness specimens are representative of the end-use component in terms of microstructure and material properties. At a minimum, the applicant should address the effects of differences between

Difference	Key Technical Information	Technical Review Guidelines
	location, spatial orientation, and frequency) depends highly on the end-use component geometry and the goal of the witness testing approach (e.g., monitoring build issues as part of process control or generating representative material properties data as part of process qualification). • When sectioning end-use geometries is not feasible, functional evaluations the relationship between the acceptability of the end-use geometries (e.g., burst tests, inspections) and the use of simplified witness specimen geometries would need to be demonstrated.	the witness specimens and the end-use component (e.g., geometry, size, location, and spatial orientation). ○ One acceptable approach would be to benchmark witness specimen results to end-use component results. • The applicant should discuss the witness testing methodology with regard to evaluation technique and frequency. **Production Process Control and Verification** • The applicant should discuss how witness testing will be used for process control and verification such that essential variables will be maintained within the qualified ranges during the production process. • The applicant can use a variety of witness specimen approaches to demonstrate process control and verification, including, but not limited to, the following: ○ monitoring build issues (e.g., incomplete spreading, delamination, or other events that may result in component rejection) ○ confirming build parameters, such as chemical composition and contamination (e.g., oxides) ○ for location-specific measurements, measuring of materials properties (e.g., strength, hardness), appropriately demonstrating how they are representative of geometry, size, location, and spatial orientation ○ confirming of expected material microstructure and characteristics (e.g., residual stress, porosity, surface finish)

<table>
<tr><th>Difference</th><th>Key Technical Information</th><th>Technical Review Guidelines</th></tr>
<tr><td rowspan="2">Thermal Post-Processing</td><td rowspan="2">• Post-processing heat treatments without hot isostatic pressing (HIP) generally are designed to provide two benefits: stress relief and/or annealing, but likely have little impact on porosity or flaws.
  ○ Stress relief heat treatments will primarily reduce residual stresses from the as-built part without otherwise affecting the microstructure or properties.
  ○ Annealing heat treatments should greatly reduce or eliminate residual stress as well as coarsen the microstructure (to improve toughness) and reduce heterogeneity in microstructure and properties.
• HIP may be beneficial for reducing residual stress, porosity, heterogeneity, and internal cracks, while also coarsening the microstructure (to improve toughness).
• For all thermal post-processing approaches, material-specific demonstration is important to identify adequate heat treatment or HIP parameters to achieve desired improvements in microstructure, properties, heterogeneity, porosity, and fabrication flaws.
• Thermal post-processing may significantly impact considerations related to the other L-DED-specific topics identified in lower rows (e.g., porosity, residual stress, initial fracture toughness).</td><td>Process Qualification
• For process qualification, the applicant should identify appropriate thermal post-processing techniques for the fabricated component and demonstrate the intended effects of thermal post-processing on the final component.
• The applicant should provide sufficient data to identify the essential variables related to thermal post-processing and demonstrate that controlling these variables within identified ranges will ensure reliable and adequate component properties and performance.
• At a minimum, the process qualification for thermal post-processing should consider the following essential variables
  ○ for heat treatment: temperature profile over time, including heating rate, cooling rate, hold time at temperature, and environment during heat treatment
  ○ for HIP: temperature and pressure profile over time, including heating rate, cooling rate, hold time at temperature, and environment during heat treatment
• The applicant should identify additional specific essential variables as appropriate.</td></tr>
<tr><td>Production Process Control and Verification
• During production, the applicant should demonstrate that process control and verification will maintain the production process within the qualified essential variable ranges for thermal post-processing.
• The applicant can use a variety of approaches to demonstrate process control and verification, including, but not limited to, the following:
  ○ testing final components on a sampling basis
  ○ witness specimens
  ○ validated monitoring of post-processing parameters during heat treatment or HIP process.</td></tr>
</table>

Difference	Key Technical Information	Technical Review Guidelines
Local Geometry Impacts on Component Properties and Performance	• The role of geometry on local microstructure and properties is one of the key differences between L-DED produced components and conventionally produced ones. • Local geometry significantly impacts thermal profiles during fabrication, which affects the local microstructure and properties. ○ For example, a thin section with relatively rapid cooling rates will likely have a much finer microstructure than a thicker section with a slower cooling rate due to more surrounding material being melted. ○ As a result, local material properties such as strength, ductility and toughness will be affected by the variation in microstructure as a function of geometry. • Post-processing and/or scan strategy refinement have the potential to minimize the local geometry impacts, however, the effects on properties and performance can vary significantly based on the geometry and materials used. • If used, witness specimens representing the thinnest section are needed to bound material properties of component. • The advantages of L-DED to fabricate components with as-built internal features can make inspection of the component features more difficult.	**Process Qualification** • Through process qualification, the applicant should provide sufficient data to demonstrate that local geometry impacts on material properties and microstructure will be addressed to ensure reliable and adequate component properties and performance. • In the absence of demonstrated post-processing or build scan strategy to minimize or eliminate the local geometry impacts, the applicant needs to use an appropriate sampling methodology during process qualification to quantify the variability in materials properties and ensure adequate performance. • The applicant should consider the following key factors affecting local geometry impacts by changing cooling rates and the resulting microstructure and properties: ○ local thickness variation ○ local size or shape • The applicant should identify additional specific key factors as appropriate. **Supplemental Testing** • The applicant should demonstrate that the local geometry impacts in an L-DED-fabricated component will not unacceptably degrade material properties and performance due to in-service aging. ○ This demonstration should be performed on a sample that is representative of, or bounds, the component's qualified pre-service condition, including post-processing.

Difference	Key Technical Information	Technical Review Guidelines
Heterogeneity and Anisotropy in Properties	• Heterogeneity generally manifests with different properties in the build direction relative to the other two directions due to the nature of the layer-by-layer build process. This impacts the microstructure and fabrication defect structure and generally creates poorer properties between build layers. • Thermal post-processing with appropriate parameters would be expected to make material properties and performance more homogeneous and similar to conventional forged materials. • For example, in as-fabricated and stress-relieved 316L, the variation in microstructure due to geometry causes preferential crack growth directions for fatigue cracks.	**Process Qualification** • Through process qualification, the applicant should provide sufficient data to demonstrate that heterogeneity and anisotropy in the L-DED build process will be addressed to ensure reliable and adequate component properties and performance. • In the absence of demonstrated thermal post-processing to minimize or eliminate the heterogeneity, the applicant needs to use an appropriate sampling methodology during process qualification to quantify the variability in materials properties and ensure adequate performance. **Supplemental Testing** • The applicant should demonstrate that the heterogeneity and anisotropy in an L-DED-fabricated component will not unacceptably degrade material properties and performance through the service life of the component, including the effects of in-service aging. ○ This demonstration should be performed on a sample that is representative of, or bounds, the component’s qualified pre-service condition, including thermal post-processing.
Residual Stress	• L-DED components typically experience significant as-fabricated residual stress. • High residual stress may result in warping, cracking, and delamination; however, these events typically can be visually detected. • In addition, residual stress can make the component susceptible to future degradation such as SCC or fatigue from the presence of high tensile residual stress on the surface. • Thermal post-processing with appropriate parameters would be expected to relieve residual stress.	**Process Qualification** • Through process qualification, the applicant should provide sufficient data to demonstrate that residual stress will be addressed to ensure reliable and adequate component properties and performance and prevent unacceptable warping, cracking, and delamination. • Post-processing through heat treatment, HIP, or both, would be expected to address residual stress but should be demonstrated. **Supplemental Testing** • The applicant should address, by testing if necessary, that the residual stresses in an L-DED-fabricated component will not significantly increase the susceptibility to in-service degradation mechanisms, such as SCC or fatigue. ○ This demonstration can be performed on a sample that is representative of, or bounds, the component’s qualified pre-service condition, including post-processing.

Difference	Key Technical Information	Technical Review Guidelines

Porosity	• Porosity is known to adversely affect fatigue life, SCC, and irradiation-assisted stress corrosion cracking (IASCC), though the precise quantitative impact depends on the material and porosity characteristics (pore frequency, pore size, pore morphology, and total void fraction).
	• Machine parameters and scan strategy refinement have the potential to address porosity concerns; however, they may vary significantly based on the geometry and materials used.
	• Porosity is more prevalent in LP-DED than LW-DED due to the internal porosity and trapped gas in powder feedstock that does not exist in wire feedstock.
	• For post-processing, HIP with appropriate parameters has been demonstrated to reduce porosity and produce properties more similar to conventionally forged materials.
		Process Qualification
		• Through process qualification, the applicant should provide sufficient data to demonstrate that porosity will be managed sufficiently to ensure reliable and adequate component properties and performance.
		• Post-processing through heat treatment, HIP, or both, may significantly reduce porosity; the applicant should demonstrate this.
		• The applicant should consider the following key characteristics of porosity when assessing porosity:
		  ○ pore density
		  ○ pore distribution (e.g., location relative to the surface)
		  ○ pore size
		  ○ pore morphology
		  ○ total void fraction
		• The applicant should identify additional specific characteristics as appropriate.
		Supplemental Testing
		• The applicant should demonstrate that the porosity in an L-DED-fabricated component will not unacceptably degrade material properties and performance due to in-service aging.
		  ○ This demonstration should be performed on a sample that is representative of, or bounds, the component's qualified pre-service condition, including post-processing.

Surface Finish	• Surface roughness is generally greater in as-built L-DED parts compared to similar forged materials. ○ The layer-by-layer nature of LP-DED combined with the tendency to weld unmelted	**Process Qualification** • Through process qualification, the applicant should provide sufficient data to demonstrate that surface roughness will be managed sufficiently to ensure reliable and adequate component properties and performance. • Post-processing through precision machining, shot peening, or other surface treatment may be able to significantly reduce surface roughness but should be demonstrated.

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<tr><th>Difference</th><th>Key Technical Information</th><th>Technical Review Guidelines</th></tr>
<tr><td rowspan="2"></td><td rowspan="2">powder particles to the component surfaces produces a rough outer surface in LP-DED.
o LW-DED typically has a bead-like surface due to the layer-by-layer deposition but does not have the added roughness of attached particles.
• Higher surface roughness can lead to reduced fatigue life and reduced SCC and corrosion resistance.
• Surface finish can be improved by post-processing such as subtractive machining, or other surface treatments.
• For components with complicated geometries, hybrid manufacturing approaches (iterating between additive and subtractive steps) may be necessary to reach all surfaces for post-processing.</td><td>Supplemental Testing
• The applicant should demonstrate that the surface finish in an L-DED-fabricated component will not unacceptably degrade material properties and performance due to in-service aging.
o This demonstration should be performed on a sample that is representative of, or bounds, the component’s qualified pre-service condition, including post-processing.</td></tr>
<tr><td>Production Process Control and Verification
• During production, the applicant should demonstrate that process control and verification will maintain the production process within the qualified essential variable ranges for post-processing.
• The applicant can use a variety of approaches to demonstrate process control and verification, including, but not limited to, the following:
o testing final components on a sampling basis
o validated monitoring of post-processing parameters.</td></tr>
</table>

Table 2B. Technical Information and Review Guidelines—L-DED 316L Material-Specific

Difference	Key Technical Information	Technical Review Guidelines

Tensile Properties	• High porosity would likely degrade tensile performance but would have a greater impact on other material properties.	**Process Qualification/Supplemental Testing**
		• For process qualification and supplemental testing, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate tensile properties for the design of the component.
		  ○ The corresponding analysis can demonstrate acceptable safety margins using approaches such as the following:
		    ▪ demonstrating equal or superior performance by comparison to tensile properties for conventionally manufactured materials
		    ▪ analyzing design requirements to demonstrate sufficient tensile properties for the component

Initial Fracture Toughness	• Limited data on 316L L-DED materials have shown significantly lower initial fracture toughness depending on post-processing than similar forged materials. This may be due to porosity or other defects that may be reduced with optimized processing parameters and thermal post-processing.
	  ○ However, 316L L-DED is still expected to have adequate initial toughness.
	• Data in representative environments is important to demonstrate that fracture toughness will be adequate to meet component design assumptions.
	• Thermal post-processing with appropriate parameters would be expected to improve fracture toughness.
		Process Qualification/Supplemental Testing
		• For process qualification and supplemental testing, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate fracture toughness for the intended function of the component.
		  ○ The corresponding analysis can demonstrate acceptable safety margins using approaches such as the following:
		    ▪ demonstrating equal or superior performance by comparison to fracture toughness for conventionally manufactured materials
		    ▪ analyzing design requirements to demonstrate sufficient fracture toughness for design and flaw evaluation purposes

Thermal Aging	• Data in representative environments is important to	**Supplemental Testing/Performance Monitoring**

Difference	Key Technical Information	Technical Review Guidelines
	demonstrate that fracture toughness does not degrade excessively due to thermal aging and will be adequate to meet component design assumptions. • Thermal post-processing with appropriate parameters would be expected to make material properties and performance more similar to conventional forged materials.	• Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate fracture toughness after thermal aging throughout the service life of the component. ○ The corresponding analysis can demonstrate acceptable safety margins using approaches such as the following: ▪ demonstrating equal or superior performance by comparison to fracture toughness after thermal aging for conventionally manufactured materials ▪ addressing uncertainties in the data on fracture toughness after thermal aging and the implications to in-service performance through conservative design assumptions, additional margins in analyses, surveillance programs, or additional performance monitoring
SCC and Corrosion Resistance	• Data in representative environments is important to demonstrate that changes in material performance due to SCC will not be degraded to a greater degree in L-DED materials than forged materials. • Post-processing with appropriate parameters would be expected to make material properties and performance more similar to conventional forged materials. • In 316L, the silicon content in the powder can create oxides that have adverse effects on SCC growth rates. Consideration should be given on oxide content in powder acceptance (virgin and recycled) criteria.	**Supplemental Testing/Performance Monitoring** • Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate SCC and corrosion resistance for the intended function of the component. ○ The corresponding analysis can demonstrate acceptable safety margins by using approaches such as the following: ▪ demonstrating equal or superior performance by comparison to SCC and corrosion resistance performance for conventionally manufactured materials ▪ addressing uncertainties in the data on SCC and corrosion resistance and the implications to in-service performance through additional performance monitoring as appropriate
Fatigue	• Without adequate post-processing, surface	**Supplemental Testing/Performance Monitoring**

Difference	Key Technical Information	Technical Review Guidelines
	roughness is known to be a greater issue with L-DED materials and can reduce fatigue life. • Fatigue properties are also dependent on post-processing heat treatment and component porosity. • Limited data suggest high-cycle fatigue life may be reduced compared to conventional 316L, while low-cycle fatigue life is comparable to conventional 316L. • Stress-relieved (without annealing heat treatment) L-DED 316L shows anisotropic fatigue strength and preferential crack growth directions due to the columnar microstructure. • Data in representative environments is important to support fatigue calculations including environmentally-assisted fatigue (EAF) in L-DED materials.	• Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments and loading conditions, to show adequate fatigue performance throughout the service life of the component. ○ The applicant can use current fatigue management approaches supported by sufficient data for L-DED 316L to manage metal fatigue (e.g., cumulative usage factors, cycle counting, EAF penalty factors). ○ The corresponding analysis can demonstrate acceptable safety margins by using approaches such as the following: ▪ demonstrating equal or superior performance by comparison to fatigue testing for conventionally manufactured materials ▪ addressing uncertainties in the data on fatigue and the implications to in-service performance through conservative design assumptions, additional margins in analyses, surveillance programs, or additional performance monitoring
Irradiation Effects	• Data in representative environments is important to demonstrate that irradiation effects will not be significantly greater in L-DED materials than forged materials. • Post-processing with appropriate parameters would be expected to make	**Supplemental Testing/Performance Monitoring** • Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate performance after irradiation (including irradiation-assisted SCC and loss of toughness) for the intended function of the component throughout its service life. ○ The corresponding analysis can demonstrate acceptable safety margins by using approaches such as the following: ▪ demonstrating equal or superior performance by comparison to irradiation effects for conventionally manufactured materials

Difference	Key Technical Information	Technical Review Guidelines
	material properties and performance more similar to conventional forged materials. • Current studies point to reduced irradiation induced defects in L-DED components compared to conventional manufacturing. However, the understanding is very limited, and research is ongoing. Additional research is likely needed to understand performance differences.	▪ addressing uncertainties in the data on irradiation effects and the implications to in-service performance through conservative design assumptions, additional margins in analyses, surveillance programs, or additional performance monitoring
High Temperature Time-Dependent Aging Effects (e.g., Creep and Creep-Fatigue)	• For high temperature operating environments (as discussed in ASME Code Section III, Division 5), data in representative environments are important to demonstrate that high temperature time-dependent aging effects in L-DED materials will be equivalent to or acceptable when compared to forged materials. • Post-processing with appropriate parameters would be expected to make material properties and performance more similar to conventional forged materials.	**Supplemental Testing/Performance Monitoring** • Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate performance after high temperature time-dependent aging effects (including creep and creep-fatigue) for the intended function of the component throughout its service life. ○ The corresponding analysis can demonstrate acceptable safety margins by using approaches such as the following: ▪ demonstrating equal or superior performance by comparison to high temperature time-dependent aging effects for conventionally manufactured materials ▪ addressing uncertainties in the data on high temperature time-dependent aging effects and the implications to in-service performance through conservative design assumptions, additional margins in analyses, surveillance programs, or additional performance monitoring

Difference	Key Technical Information	Technical Review Guidelines
Weld Integrity	• Data in representative environments is important to demonstrate that welds with L-DED base materials will perform similarly to those with conventionally manufactured base materials.	**Supplemental Testing/Performance Monitoring** • Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate performance of the weld throughout the service life of the component. ○ This analysis can be informed by relevant experience and knowledge of performance of welds of conventional materials along with potential limited -scope testing on welds of L-DED materials. ○ The corresponding analysis can demonstrate acceptable safety margins by using approaches such as the following: ▪ demonstrating equal or superior performance by comparison to weld performance for conventionally manufactured materials ▪ addressing uncertainties in the data on weld performance and the implications to in-service performance through conservative design assumptions, additional margins in analyses, or additional performance monitoring
Weldability / Joining	• There is very limited published information on the results of traditional joining methods being used on L-DED components • Higher oxygen content, residual stress, and microstructural segregation may affect the optimal parameters for welding on L-DED 316L compared to conventional 316L. • Weldability should be demonstrated for L-DED materials, but the existing welding standards and demonstration processes should be sufficient.	**Process Qualification/Production Process Control and Verification** • Through process qualification and production process control and verification, the applicant should provide sufficient data to demonstrate that weldability using traditional arc welding or other joining processes that may be required for component installation in service can be performed consistently and reliably with sufficient quality to meet Code acceptance criteria. ○ This should include careful consideration of unique aspects of L-DED-fabricated materials compared to traditional manufacturing methods, including local geometry impacts on material properties (e.g., fracture toughness) and heterogeneity/anisotropy, which are described in greater detail previously in this document.