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SOME CHALLENGES REGARDING QUALIFICATION OF ADDITIVE MANUFACTURING COMPONENTS FOR A NUCLEAR USE – NUCOBAM PROJECT

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ABSTRACT
In the last decade, additive manufacturing (AM) technology has progressed significantly, and thus found its way into a number of industries. AM is particularly interesting for manufacturing components with complex geometries, which if produced via conventional manufacturing methods involve significantly more manufacturing steps and longer lead times for a limited number of pieces. The nuclear industry is no exception and has developed roadmaps that outline key steps that can potentially allow the usage of AM to produce nuclear reactor components. In this context, standardization can appear as a straightforward way to accelerate the qualification of these processes for a nuclear use. It is the overall goal of the project NUCOBAM (Nuclear Components based on Additive Manufacturing) to address the technical challenges associated with the production of reactor components via AM. The finality of the project is to develop a methodology for qualifying components produced via AM that complies with nuclear codes and standards. The AM method and alloy in scope of the project are Laser Powder Bed Fusion (L-PBF) and the stainless steel 316L. This paper presents the NUCOBAM project in more detail, including the challenges it reveals regarding standardization and the perspectives of qualification methodology.

Keywords: Additive Manufacturing, Nuclear codes, qualification

NOMENCLATURE

AM	Additive Manufacturing
L-PBF	Laser Powder Bed Fusion
P-AMPS	Preliminary Additive Manufacturing Procedure Specification
AMPS	Additive Manufacturing Procedure Specification
SDO	Standard Development Organization
WP	Work Package
IBAMS	In-pile Behaviour of Additively Manufactured Samples
NDE	Non-destructive examination
UT, VT	Ultrasonic Testing and Visual Testing
SSRT	Slow Strain Rate Testing
SCC	Stress Corrosion Cracking
PIE	Post Irradiation Examination
KLST	Kourou Low Stress Tube
HIP	High Isostatic Pressure
TEM	Transmission Electronic Microscopy
QC	Quality control

1. INTRODUCTION

Additive manufacturing (AM) processes have undergone rapid development and deployment in many industries. Those processes are quite powerful to manufacture complex parts with limited costs both in materials and in global manufacturing time. The nuclear industry has developed a strong interest on the new possibilities offered by AM technologies, especially to tackle component obsolescence challenges and to manufacture and operate new components with optimized designs. However, the deployment of such processes depends on the demonstration of equivalence in terms of quality and safety of AM components compared to materials and methods typically used in the nuclear industry. To reach this demonstration, a European project named NUCOBAM (Nuclear Components based on Additive Manufacturing) has been launched, one of the main objective being to consolidate elements which support the standardization of the L-PBF technique. In the following sections, the challenges for the implementation of L-PBF process in nuclear codes and how NUCOBAM addresses them will be explored.

2. CHALLENGES OF AM STANDARDISATION IN NUCLEAR CODES

Since the beginning of the development of AM technologies, standardization has been put forward as an efficient tool for the deployment of those processes [1] and today, numerous standards are available (or under development) to cover the different aspects of AM. The needs for a specific action regarding nuclear applications were also identified [2]. In this context, it is evident that there is a need for users to identify and to define the key requirements that will permit the introduction of AM in nuclear codes.

2.1 AM SPECIFICITIES REGARDING NUCLEAR CODES

The first observation is that AM seems to be very similar to welding techniques. The following table identifies a set of technologies of interest to be used for manufacturing of a component.

Category		Energy source	associated technology
Powder Bed Fusion (PBF)		Laser beam	L-PBF (Laser Power Bed Fusion)
			DMLS (Direct Métal Laser Sintering)
		electron beam	EBM (Electron Beam Melting)
Directed Energy Deposition (DED)	Powder	Laser beam	LDMD (Laser Direct Metal Deposition)
		electron beam	EBM (Electron Beam Melting)
	Wire	Laser beam	LWAM (Laser Wire Additive Manufacturing)
		electron beam	EBAM (Electron Beam Additive Manufacturing)
		Arc	WAAM (Wire and Arc Additive Manufacturing

TABLE 1: TECHNOLOGIES OF INTEREST

The analogy with welding, especially regarding feedstock and energy source of melting, appears clearly. On the other hand, the extension of AM, not limited to the junction between two parts, leads to additional requirements when compared to those needed for welding qualification. The table below illustrates the different domains to be covered in the case of process and part qualifications (from RCC-M [3]), where correspondence between both types of qualification are indicated with a common color (Table 2).

Contents of a Welding qualification	Contents of a Part qualification (RCC-M , M140)
	Qualification report for product
Acceptance of filler materials	Manufacturing programme (main parameters including raw material)
Welding Procedure Qualifications (WPQ)	Verification of product properties
Qualification of welders and operators	Acceptance tests for product
Qualification of filler materials	Qualification report for shop
Technical qualification of production workshops	Facilities
Production welds	Personal and management
	Industrial experience

TABLE 2: WELDING VS PRODUCT QUALIFICATION CONTENT

Neither a welding qualification nor a part qualification as defined in nuclear codes such as the RCC-M can be applied as it is to AM. Therefore, there is a strong need to define an AM-specific qualification methodology in the different nuclear codes.

2.2 REQUIREMENTS FOR STANDARDISATION

The requirements and the associated documents to be provided are described by Standards Developing Organizations (SDOs) as exemplified in the RCC-M, which includes a dedicated part for new processes as depicted in figure 1:

M 116 SPECIFIC USE OF A NON-REFERENCED MANUFACTURING PROCESS

Manufacturing processes not referenced by the RCC-M can exceptionally be proposed by the Manufacturer, for a particular application. In these conditions, and prior to the procurement of the materials, the Manufacturer must submit the following items to the Contractor for approval:

a) A procurement specification; for this purpose, it shall most frequently use a similar existing Reference Technical Specification, or a compatible standard, stating the options systematically adopted

b) A first part qualification, according to the principle described in M 140

c) A document package justifying the use of the grade for the targeted application. This document package shall include at least the following items:
- References to the existing standards and technical specifications
- The data needed for design
- Evidence that the material obtained by this new manufacturing process is suitable to be employed for the targeted application
- Evidence that the acceptance (destructive and non-destructive tests) is appropriate for the inspections of the products resulting from this new manufacturing process
- Performance under the service conditions, for the targeted application
- Experience feedback: status for similar applications.

FIGURE 1: EXAMPLE OF REQUIREMENTS FOR NON-REFERENCED MANUFACTURING PROCESS IN THE RCC-M CODE

The qualification objectives, established through the qualification document, are to:
- demonstrate the capability to manufacture the component,
- define the validity domain of the manufacturing program,
- check that the final component has the required properties,
- define the relevant delivery conditions and criteria (witness sample).

The European Commission's main motivation was to create a project to structure and gather the technical documentation needed for AM standardization. The aim is to establish a document package for standardization (ref: *point c* of figure 1), by evaluating end-to-end requirements, from the theoretical qualification process, through parts manufacturing, to testing.

3. NUCOBAM PROJECT

3.1 NUCOBAM description

The project consortium comprises 13 partners, and is organized into seven work packages (WP), define as follows [8]:

- WP1 focuses on the methodology for AM qualification standardization, and develops it.
- WP2 handles the AM process qualification and the aim is to create a general methodology for qualifying L-PBF processes.
- WP3 gathers the Non Destructive Examinations (NDE) and evaluation of mechanical properties and microstructure, to ensure the capability to decide of the qualification as processed.
- WP4 is dedicated to the assessment of the In-pile Behaviour of Additively Manufactured Samples (IBAMS) and deals with microstructure characterization, determination of the mechanical properties, irradiation conditions (fluence, temperature…) and documentation.
- WP5 handles the performance assessment of ex-core user case: valve component produced by L-PBF process.
- WP6 (dissemination and exploitation) and WP7 (Project Management) ensure support functions of the project.

3.2 NUCOBAM principles regarding qualification

To establish the qualification methodology, the main idea is to take advantages of the existing approved standards already developed for AM in other sectors, and also to be in line with the other on-going developments existing around the world.

The general principle is illustrated following figure 3.

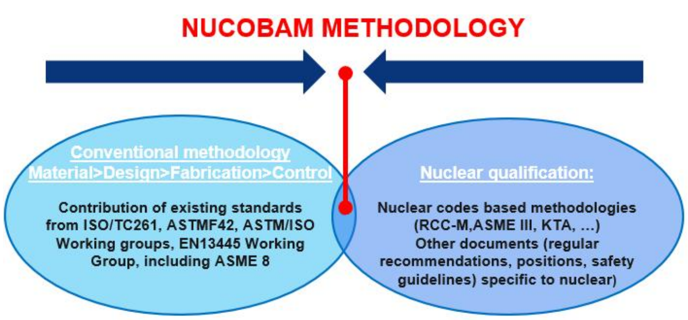

FIGURE 3: METHODOLOGY PRINCIPLES

The first step of the process is thus dedicated to the identification of standards, and other pertinent areas of interest.

A large variety of relevant standards and guidance on AM are available, covering all aspects of AM were reviewed. Existing information include component design, metallic powder handling and characterization, the AM process itself, and subsequent qualification, post-heat treatment, and documentation requirements, in conjunction with relevant standards such as EN ISO ASTM 52900 family of standards, AMS standards (AMS 7002, AMS 7003, AMS 7032), various ASTM standards (e.g. ASTM F3184 [6]), and AWS D20.11D20.1M [7].

Consequently, nearly 50 standards were considered as relevant for the qualification of the process. Correspondingly, the final methodology would have to refer, as much as possible, to the most relevant requirements and criteria.

The NUCOBAM project also defined the main steps and associated documentations to be established prior to manufacturing a component as illustrated in figure 4 below.

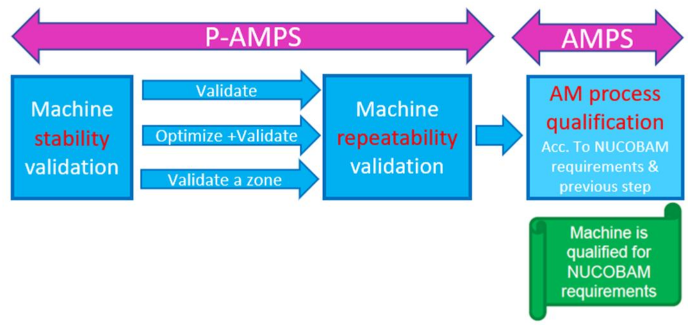

FIGURE 4: PROCESS QUALIFICATION STEPS

The process stability is assessed by measuring the variability of the material properties of the specimens issued from the same job according to their positioning on the build platform (Printed job to check and validate machine stability). The assessment of process repeatability is carried out by measuring the variability of the specimens' properties from one job to another, using the same machine and process parameters (Printed job to check and validate machine repeatability i.e. check that there is no significant discrepancy with the stability platform in terms of material performance). The stability and repeatability steps enable define and set of relevant job parameters and enhance confidence in the results. The AM qualification step ensures that the requested quality is achievable. It is followed by a product validation platform with the representative part to validate also that the design can be manufactured.

The following figures illustrate the stages of the qualification process in WP2 [8]:

Stability Repeatability AM process qualification

FIGURE 5: QUALIFICATION STEPS REALISATION

To illustrate the potential influence operator preparation and different machines, four manufacturers (Nuclear AMRC, CEA, ENGIE Laborelec and VTT – see table 3) are part of the

NUCOBAM project and implement the established WP2 processes.

NUCLEAR AMRC	CEA	ENGIE Laborelec	VTT
Renishaw	SLM Solutions	SLM Solutions	SLM Solutions
AM250 single laser	SLM280HL® single laser	SLM500® quad-laser	SLM125HL® single laser
240x240x300mm m³ (l x L x H)	280x280x350m m³ (l x L x H)	280x500x350m m³ (l x L x H)	125x125x125m m³ (l x L x H)
Argon as inert gas	Argon as inert gas	Nitrogen as inert gas	Argon grade 5.0 as inert gas

TABLE 3: CHARACTERISTICS OF MACHINES OPERATED BY NUCOBAM MEMBERS

The two components are built after the qualification phase:
Debris filter was built by Nuclear AMRC:

- Designed by Framatome,
- Two build platforms of the debris filter component,
- Solution anneal at 1066 °C.

Valve body was built by ENGIE Laborelec:

- Designed by Ramen Valve and ENGIE Laborelec,
- Three build platforms of the valve body component,
- Solution anneal at 1066°C.

In total, 780 specimens will be tested (684 in the frame of WP3 and 96 irradiated specimens in the framework of WP4).

Tests on specimens will cover:

- Material characterizations as manufactured,
- Non-destructive examinations,
- Material characterizations after thermal ageing,
- Material characterizations after irradiations.

Several types of examination and characterization are implemented:

- Characterisation of AM material via NDE (tomography, UT, X-ray, VT, checking for material inhomogeneities),
- Material test programme on as-received AM material and thermally-aged (18 months at 450°C) AM material: tensile tests, hardness, microstructure and grains size, Charpy impact, fracture toughness, fatigue, inter-granular corrosion, stress corrosion cracking (SCC) testing (U-bend, SSRT), creep,
- Post Irradiation Examinations (PIE) of irradiated specimens (KLSTs, tensile and micrography specimens), irradiation will be performed by SCK-CEN in BR-2 reactor, in Mol.

3.3 First results

The preliminary methodology report based on the selection of relevant standards has been issued.

The following chapters are addressed:

1. General (Scope, quality & personnel qualification, traceability of specimens and documentation).
2. Terminology (essentially referring to standard AM terminology and powder metallurgy according to ISO/ASTM 52900, ISO/ASTM 52921, ASTM F2924, ASTM B243 + defining new terms).
3. Documentation (equipment specifications, powder acceptance specifications, component manufacturing plan & reports, …).
4. Powder Procurement
   - Documentation & traceability (i.e. powder acceptance specification, statements of conformity, material certificates) ;
   - Sampling (for powder characteristics analyses);
   - Powder characteristics (i.e. particle size distribution, chemical composition, densities, morphology, flowability);
   - Contamination;
   - Packaging, handling & storage;
   - Re-use of powder.
5. Qualification of the AM Process
   - Preliminary AM procedure specifications (essential & non-essential variables for L-PBF, job control plan, job sheet, CAD file, job configuration file, parameter set file, laser scan trajectory file, machine file);
   - Process stability (dimensions & number of samples, stability assessment tests, …);
   - Process repeatability;
   - AM process qualification platform & tests;
   - Product validation platform;
   - Procedure qualification records.
6. Design Data.
7. Manufacturing of Component & Test Specimens
   - Equipment specifications;
   - AM procedure specifications;
   - Component manufacturing plan (QC);
   - Quality monitoring (manufacturing control system: witness samples, in-situ control, printer log files, examination of final qualified part (ref. to Section 10)).
8. Heat Treatment
   - Environment (Atmosphere or gas) and procedure (e.g. temperature, soaking time, cooling) for 4 different conditions: Stress relief, solution annealing, hot isostatic pressing, as built.
9. Inspections & Tests
   - Chemical analyses;
   - Microstructure;
   - Mechanical properties (tensile, hardness, impact toughness, density).
10. Finishing of AM component (Cleaning, pickling & passivation, removal of support material (machining, EDM), grinding, polishing).
11. Examination (NDE of finished component).

On this basis, the AM process qualification and test coupon manufacturing have been performed (in order to address §4 and §5 detailed in the methodology report).

Within the scope of WP3, the initial results of the characterization reveal are presented in the general presentation of NUCOBAM [8]. In the context of all the heat treatments applied, figure 6 shows the different microstructure observed.

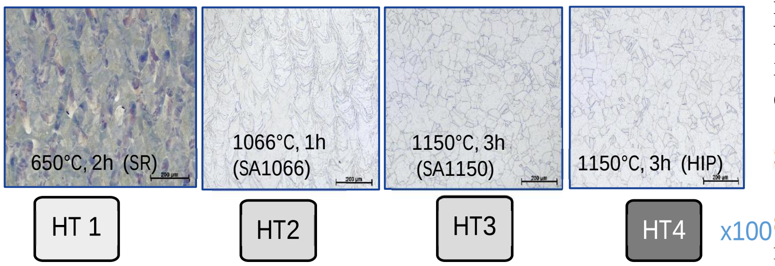

FIGURE 6: METALLOGRAPHIC STRUCTURES

Some components have also been built and tests on un-irradiated specimens have been conducted on witness samples (some specimen are irradiated meanwhile in SCK CEN facilities (WP4) and other specimens are thermal aging at the EDF Lab les Renardières facility (WP5)). Figure 7 illustrates the main components studied during the project, along with the witness samples present on the platforms for the component qualification.

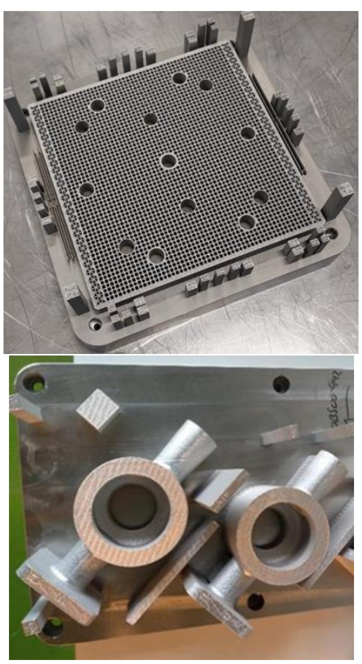

FIGURE 7: MANUFACTURED COMPONENTS

In the context of WP4, irradiation of specimens from additive manufacturing, including Charpy miniature samples, flat tensile samples and TEM samples, has been successfully conducted in the BR2 reactor. Currently, the post-irradiation examination is in progress.

In the framework of WP5 [9], valve bodies are assembled using conventional internal components. The valve undergoes static test. Subsequently, a burst test is conducted, and an expertise of the as tested valve will be performed through inspections and extraction of samples for further analyses.

It is noteworthy that the validation platforms proved to be highly beneficial for the valves, allowing for the anticipation of measured retractions and deformations resulting from residual heat tensions. This foresight was instrumental in avoiding issues in the final components, facilitated by slight modifications in the design and platforms.

3.4 Next steps

The final steps include complete characterization of specimens and parts to validate the values included in the methodology report and to establish the proposal texts for nuclear codes as illustrated below.

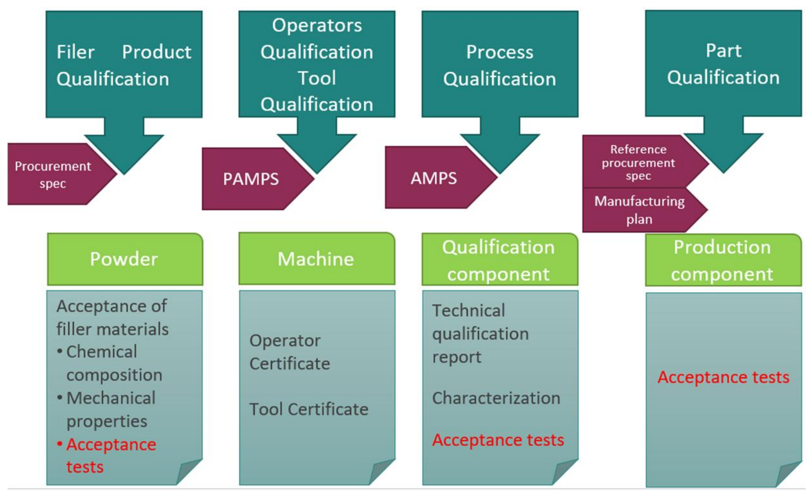

FIGURE 8: EXAMPLE OF INPUT DATA FOR THE COMPLETION OF THE QUALIFICATION METHODOLOGY

Concurrently with the finalization of the methodology, two documents for RCC-M and ASME are in preparation (figure 9). The final task of the WP1 is to proposed code evolutions (submission not included in NUCOBAM).

The ASME text proposal links the chapters in the project methodology to the ASME document PTB-13-2021 [15].

More results are expected during 2024 [8].

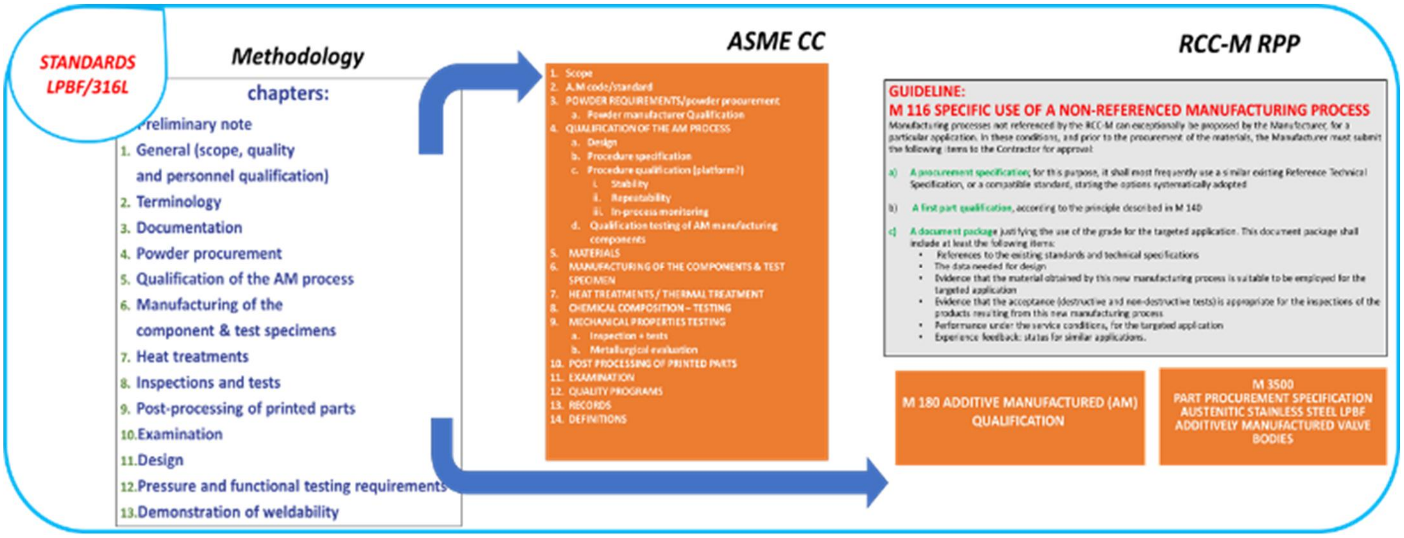

FIGURE 9: ASME CODE CASE AND RCC-M DOCUMENTATIONS IN PREPARATION

4. CONCLUSIONS

The nuclear industry has specific requirements in terms of quality assurance and qualification that could make the transfer from R&D to industry really challenging. A way to facilitate the transition process is via standardization and a nuclear code. The NUCOBAM project aims to facilitate the standardization of AM components to be implemented in nuclear codes by proposing solutions to requirements already defined in existing nuclear codes (RCC-M for instance) for the introduction of a non-covered manufacturing process. The first results of the project are promising and corroborate the proposed methodology.

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REFERENCES

[1] Standardization Roadmap for Additive Manufacturing version 2.0, America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC), June 2018.
[2] Roadmap for Regulatory Acceptance of Advanced Manufacturing Methods in the Nuclear Energy Industry, Nuclear Energy Institute, May 2019.
[3] RCC-M, Règle de conception et de construction des matériels mécaniques des îlots nucléaires REP, Afcen, édition 2020.
[4] Horizon 2020 project NUCOBAM : NUclear COmponents Based on Additive Manufacturing, www.nucobam.eu.
[5] Oliver Martin, *The NUCOBAM Project – Use of Additive Manufacturing in Reactor Component Manufacturing, 16th FORATOM-IAEA Event Management Systems for Sustainable Nuclear Supply Chain*, September 7-9, 2021.
[6] F3184-16 Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion.
[7] AWS D20.1/D20.1M, Specification for Fabrication of Metal Components using Additive Manufacturing.
[8] M. Bourgeois, G. Leopold, NUCOBAM project, nuclear components based on additive manufacturing – PVP2024-122057.
[9] N. Bertelle, R. Hernandez, A. Fernandez-Viña, R. MISLER, Performance assessment of additive manufacturing components for an ex-core nuclear user : valve component – NUCOBAM project – PVP2024-123236.
[10] ASME PTB-13-2021: criteria for pressure retaining metallic components using additive manufacturing.
[11] EN ISO ASTM 52900, Additive manufacturing – General principles.
[12] AMS 7002 – Process Requirements For Production Of Metal Powder Feedstock For Use In Additive Manufacturing Of Aerospace Parts.
[13] AMS 7003 – Laser Powder Bed Fusion Process.
[14] AMS 7032 – Machine Qualification For Fusion-Based Metal Additive Manufacturing.
[15] ASME document PTB-13-2021: *Criteria for pressure retaining metallic components using additive manufacturing*.

