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Development of a Procedure for Risk-Based Qualification of Additively Manufactured Components: Adopting to Oil and Gas Industrial Applications

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Abstract: Recent advances in additive manufacturing (AM) technology provide the potential for on-demand and rapid production of spare parts during urgent repair times. Recently, big oil and gas companies have shown early progress in using additive technology in manufacturing specific heat exchangers, downhole cleanout tool nozzles, offshore risers, gas turbine nozzles, and subsea chemical stick injection tools. Despite the mentioned progress, the current adoption level of additive technology for the offshore oil and gas industry is very limited. Non-destructive and destructive evaluation methods of additively manufactured metallic components have been studied extensively. However, the technique selection procedure and scope of the required test methods have not been studied sufficiently. This paper discusses various elements related to the qualification of additively manufactured components for application in the oil and gas industry. A risk-based qualification method for identifying the scopes of required non-destructive and destructive tests and the resulting qualification procedure for additively manufactured spare components in offshore oil and gas applications is suggested.

Keywords: additive manufacturing; offshore industry; spare parts; qualification; non-destructive testing

Citation: Abbaszadeh, B.; Ratnayake, R.M.C.; Eskandarzade, M.; Ajri, M.; Rasouli, H.; Najafi Ershadi, M. Development of a Procedure for Risk-Based Qualification of Additively Manufactured Components: Adopting to Oil and Gas Industrial Applications. *Appl. Sci.* **2022**, *12*, 10313. https://doi.org/10.3390/app122010313

Academic Editor: Abílio Manuel Pinho de Jesus

Received: 1 August 2022
Accepted: 21 September 2022
Published: 13 October 2022

1. Introduction

Offshore oil and gas production facilities in the entire world are subjected to many deterioration mechanisms. Replacement of failed components with new parts is one of the main strategies in repair and maintenance management systems [1]. The spare parts supply chain in the operating and maintenance (O&M) process is of great importance for offshore industries, as any delay in spare parts supply can be the cause of a substantial increase in costs due to increased shutdown times, loss of production, and labor work [2]. Warehousing and capital costs make it uneconomic to store all spare parts in stock, therefore, the introduction of alternative technologies for the supply chain process is essential. Companies usually order their needs for spare parts from vendors located thousands of kilometers from the destination facility. Generally, any purchase order requires considerable time, the use of heavy transportation, and regulatory work between countries before the goods reach the consumer [3]; this is even more critical for slow-moving components. Therefore, rapid on-demand production with reduced transportation, labor, and other related waste costs with production in customer vicinity is a very attractive technology for spare parts supply chain managers in the petroleum industry. This is feasible by utilizing additive manufacturing (AM) technology (sometimes called 3D-printing technology). Using AM, it is not required to store physical assets, instead, CAD formats of the components are stored in a digital library and are sent for manufacturing, close to the customer, based on demand, e.g., in repair or replacement times [4]. During the COVID-19 pandemic and the associated border restrictions between countries, demands for AM components grew [5]. AM helps the production of many customized components based on individual customer needs; for example, in drilling operations, AM can provide more customized spare parts, helping to ensure particular old rig compliance, where the vendor no further supports that specific version of the product [6]. Despite this, there are many reports regarding the application of AM technology in the manufacturing of high-strength metallic parts, but there is no evidence of using AM technology in petroleum operations on an industrial scale—this is because there is no internationally accepted procedure for qualifying these materials for oil and gas application. Recently, many non-destructive and destructive methods have been developed to evaluate the quality of additively manufactured components. An overview of the applicable non-destructive techniques for metallic additively manufactured components can be found in the literature [7,8]. The application of ultrasonic and X-rays microtomography in inspection of additively produced metal components has been investigated by Kim et al. [9] and Xavier et al. [10], respectively. Despite much research conducted in the field of non-destructive and destructive test methods of additively manufactured components, the number of studies with a focus on determining an acceptable inspection and test plans are limited. A specific qualification of aluminium alloy parts produced by Raytheon's metals AM technology for safety-critical applications is presented in work by Byron [11]. To date, there is no published paper that discusses the inspection and test plan and the qualification procedure of the additively manufactured spare parts for application in the offshore oil and gas industry [12,13]. There are particular standards and recommended practices for risk-based inspection or qualification. The API-RP-580 and 581 are examples of such recommended procedures in the oil, gas, and petrochemical industries. The risk-based qualification is strongly dependent on damage mechanism identification. Although damage mechanisms in hydrocarbon-carrying pipelines are classified for engineering materials (e.g., API-571), the potential damage mechanisms for additively manufactured components requires continued research and investigation. Process-induced lack of fusion, porosity, surface defects, and residual stress are examples of risk drivers that can be found exclusively in the AM process. These particular damage mechanisms of AM process require commensurate inspection methods and imply specific qualification processes. This study attempts to fill the gap between additive manufacturers and end-users in the oil and gas industry by introducing the required non-destructive and destructive test plans. Through this study, the procedure for qualifying the additively manufactured spare parts for use in offshore oil and gas applications is proposed. The proposed risk-based qualification procedure helps the qualifying societies and material selection experts to assess the suitability of additively manufactured components for offshore applications. During the present risk assessment work, few experiments are performed to assess the corrosion behavior of the additively manufactured components. Based on results from the risk-based qualification process, the qualifying agencies can concentrate on more critical inspection stands and therefore make optimal use of budget and resources. SAE 316L material grades have wide applications in the offshore industry. For this reason, in this study, the corrosion concerns of the qualification process for SAE 316L material grade processed by selective laser melting (SLM) technique are discussed in detail.

2. Industrial Demand and Qualifying Challenges

Additively manufactured materials have potential applications in oil, gas, and petrochemical industries as pressure envelopes, functional components, or structural parts. These components and structures suffer from damages induced by severe environmental conditions, especially in North Sea platforms. In this regard, jackets, pipeline end terminations (PLETs), and drilling support modules are example components that may indicate intermittent failures during their life cycle. Besides, there are many fluid-carrying components that can be repaired or replaced by additively manufactured components. However, there is still no long-term field experience in using AM components in the offshore industry. Accordingly, our information about the potential active damage mechanisms for these material types is limited and less reliable. Additive manufacturing is a de-centralized manufacturing process that makes the tracing of the material production difficult for qualification purposes. In addition, this process is not a mature manufacturing process and still suffers a lack of reproducibility and uncertainty of quality control [14]. It is notable that AM technologies were perceived as immature by nearly 50% of security and defense organizations by 2018 [15]. In addition, the business models for additive manufacturing technology are still immature for large-scale adoption [16,17]. The certifying procedures for AM require continuous work to better adaptation of the technology in various industrial fields [12].

To convince customers from the oil and gas industry to shift from conventional manufacturing techniques to additive technology, they need to be assured that additively manufactured components satisfy minimum requirements imposed by codes, standards, and regulations. It means that uncertainties induced by mechanical strength or corrosion resistance for additively manufactured materials should fall within the pre-specified ranges. The fundamental problem is that the additive manufacturing supply chain is less understood than conventional processes. Many defects and characteristics of the additively manufactured parts are still under investigation [18]. X-ray diffraction [19], laser diffraction [20], digital imaging [21], in-situ AM process monitoring [22], ultrasonics [23] are some examples of non-destructive testing in additive manufacturing process. At the moment, additively manufactured components are qualified based on a one-by-one evaluation process. This procedure is neither economic nor effective. In this study, the aim of developing a qualifying procedure is to define a process to systematically identify relationships between the manufacturing process–microstructure product performance of the additively manufactured materials. Table 1 compares the qualification challenges for additively manufactured and conventional spare parts. Risk-based inspection is one of the cost-effective methods for defining the scopes of different non-destructive testing methods and developing inspection and test plans [24]. This study suggests a qualifying procedure and helps to develop an inspection and test plan for metallic AM components based on a risk assessment concept.

Table 1. Qualifications features of additive and conventional manufacturing process.

Qualification Step	Conventional Manufacturing	Additive Manufacturing
Technology assessment	Mature Normally repeatable Homogeneous microstructures Properties are isotropic Dense structure	Immature Not-repeatable Inhomogeneous microstructures Properties are anisotropic Porous structure
Qualification of feed stocks	Mature Many successful experiences reported in the industry Mostly in rod and billet form	Immature Less experienced in the industry Mostly in the form of liquid, powder, wire, filament, sheet, etc.
Manufacturing procedure qualification	Most of the parameters remain unchanged for different vendors	Drastic changes are required when a manufacturer changes
Qualification of final product	Sufficient field data is available Failure modes and types well studied Test methods are normally mature and reliable	Less experienced in the industry Failure modes and types are still under question Test and evaluation methods are not standardized.

Another major challenge and concern about additive manufacturing is the protection of intellectual property (IP) [25]. These concerns include questions around the ownership of geometry and designs, the probability of copying parts by scanning and then printing them, and concerns about the production of fake components. Fortunately, some of these concerns have been resolved or even addressed by current legal provisions [26,27].

3. Main Concerns in AM Quality Control

Additive manufacturing technology was first introduced in the USA during the 1980s. The AM term encompasses all methods which shape the final product using a layer-by-layer addition of materials. In the last 30 years, AM processes and equipment showed fast growth, and nowadays, more than 20 AM processes have been introduced. AM techniques can process a wide range of materials, including polymers, composites, and metals. In the case of metallic products, there are two main branches of AM processes, powder bed fusion-based technologies (PBF) and directed energy deposition (DED) based technologies, however, binder jetting has also shown limited capability in producing metallic parts. The main subcategories of DED are laser-engineered net shaping, direct metal deposition, electron beam freeform fabrication, and arc-based AM. Furthermore, the subcategories of PBF technology are selective laser sintering (SLS), electron beam melting, and LaserCUSING. These techniques can differ in terms of principle processing material, heat source, and economic advantages. Research is still ongoing to minimize the operational cost, increase the quality of the final product, and increase the production speed and flexibility of the individual AM machine to produce parts with versatile material types and geometries. Rapid growth in AM techniques, equipment, and the introduction of new generations of AM processes implies that the qualification procedure shall be dynamic and flexible to cover all new equipment and technique types.

The additive process is a kind of micro-welding that uses powders and beam power to melt the powders and produce a track weld [28]. Figure 1 shows the schematic of track production in the SLS manufacturing method. The quality of the track directly affects the quality of the final product.

Therefore, the qualification of the build can be compared with the qualification process of the conventional welding process. In an additive manufacturing system, the parameters such as powder quality, heat input in the melt pool, beam power, beam diameter and intensity, beam scan pattern (spiral, meander, etc.), bead cooling rate, powder preheat, track height, track overlap, track width, post-processing, etc., affect the quality of the micro-welding process.

In addition to the process and machine type, the quality of the feedstock is of significant importance for producing high-quality additively manufactured samples. Studies have shown that the powders with spherical shapes are much preferred to obtain uniform distribution and packing of the powders because of the advanced flowability and spreading characteristics [29]. In addition to powder shape, the powder chemical composition can also affect the quality of the AM parts. For some alloys, vaporization of some elements from powder due to highly localized heat input can be problematic.

Poor quality of the powders originating from the chemical composition of the powder [31], powder size distribution (PSD) [32], moisture content, pore size and shape [33], surface area, microstructure, thermal properties, density, flowability, and morphology can lead to undesired impurities, precipitations and other microstructural deficiencies such as cracks. Furthermore, the powders' humidity content is significant in the overall quality of the manufacturing process. Powders may become wet during the handling and storage stages or due to a poor powder-making process. During the manufacturing process, the water content of the powders is decomposed into oxygen and hydrogen atoms after exposure to beam power. As a result of the high cooling rate, the atomized water components cannot escape from the melt and are trapped inside the material during the solidification process. Porosities in original powders were created during the "powder making process", mostly remain inside the finished material even after the re-melt process during the additive manufacturing process. Sometimes, post-processing is required to control the humidity content of the powders to reduce the initiation of the porosities. Moreover, there is optimal particle size distribution for each additive manufacturing technique. Therefore, powder size distribution is another important parameter for evaluating the quality of the feedstocks. Because of all these challenges, at the moment, pre-alloyed powders for additive manufacturing applications are available only for limited material grades. However, recent studies attempt to increase the range of the powder types and applicable material grades. The continuous advances in powder production and usage make the qualification process challenging.

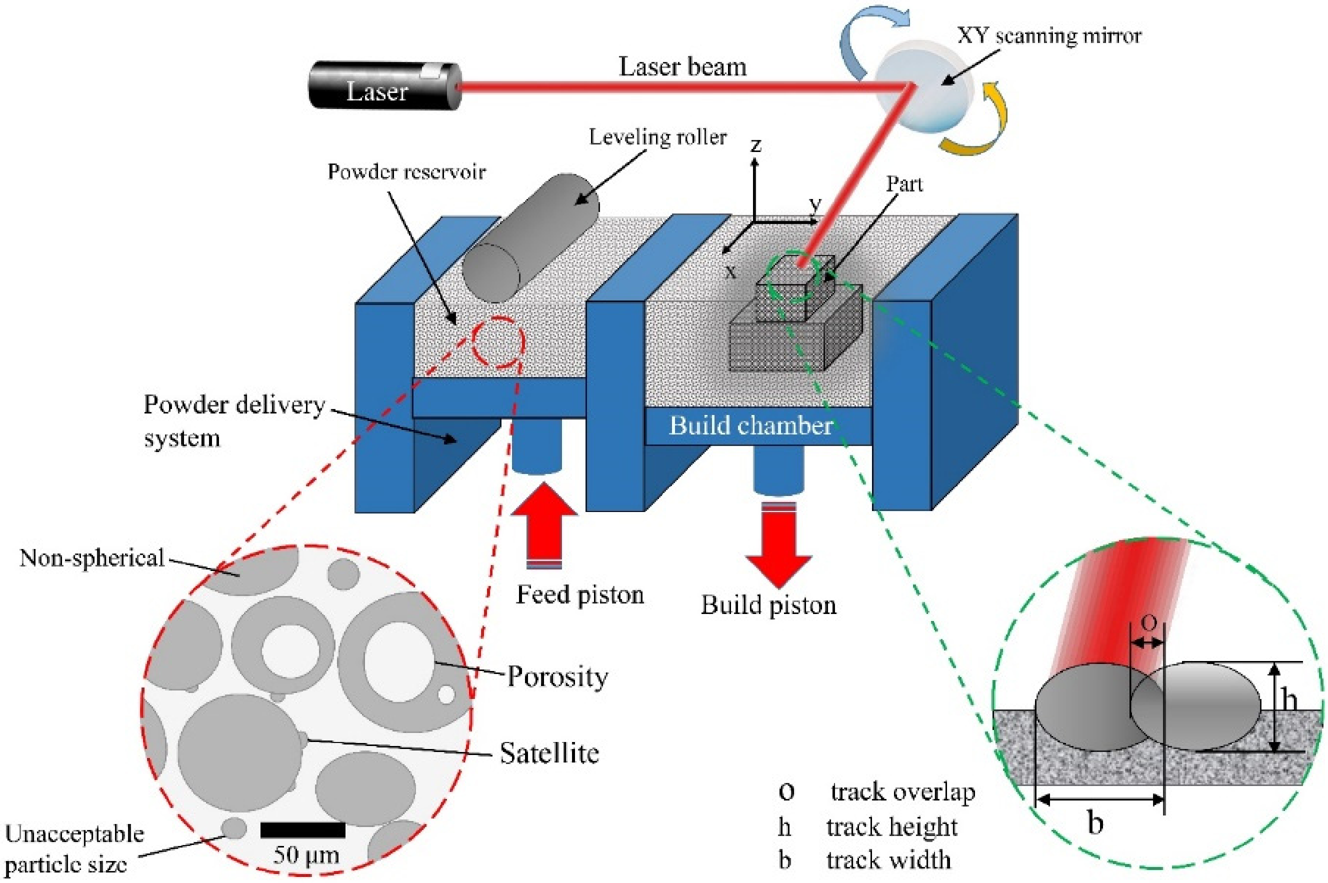

Figure 1. Schematic of selective laser sintering (SLS) [30].

4. The Qualification Procedure for AM Components

Additive manufacturing techniques produce exceptional microstructure and mechanical properties, which is different than those of traditional manufacturing techniques [34]. Many qualification procedures and standards are already developed for conventional manufacturing methods that are used as a base for developing qualifying methods for additively manufactured components. Using these available qualification procedures helps to enhance consistency and to ensure that the qualification procedure for AM components complies with other available codes and standards. Figure 2 indicates the qualification sequence for AM process. According to Figure 2, the qualification process starts by assessing the technology and raw material (powder), and continues with evaluating the manufacturing procedure, finally ending by qualifying the material performance for the intended application. As is clear, some qualification activities are required to be performed before the build job begins. Table 2 summarizes the most important parameters which should be assessed before the start of build job. After the pre-processing step is successfully qualified, the build job starts. In this step, the subject matter engineer must carefully define the processing parameters to obtain desired microstructure and material properties.

During the qualification process, all steps should be recorded in the manufacturing procedure specification (MPS) document of the project. This is critical for production repeatability and reliability, as the quality of the AM parts substantially relies on process controls. Here, the qualification procedure works as a formal validation and approval of the process controls and ensures that the manufacturing procedure is feasible. The main concerns in the manufacturing procedure qualification sequence are presented in Table 3.

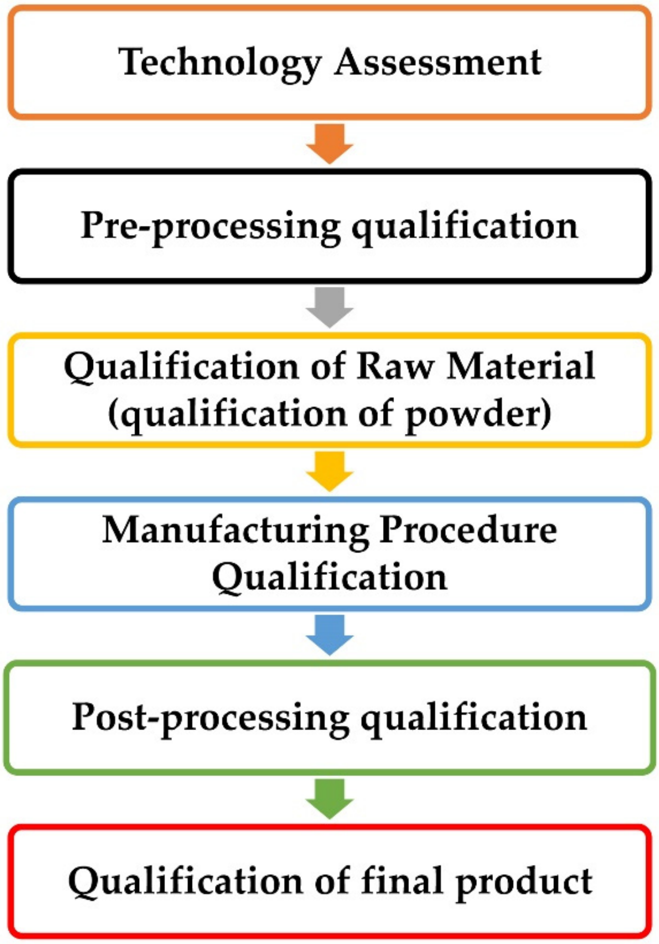

Figure 2. Five qualification sequences for additively manufactured parts.

Table 2. Qualification parameters before the start of the build job.

Qualification Step	Main Parameters to Be Controlled
Qualification of raw material	Powder handling and storage, verification of virgin powder, usage, reprocessing, reuse limits and controls, powder chemistry and morphology.
Technology qualification	Process type, machine type, calibration requirements, complete documentation of operating condition, Diagnosis of equipment, routine controls.
NDE requirements	Qualify the probability of detection and the capabilities of the used in-situ monitoring techniques.

Table 3. Qualification parameters in manufacturing procedure qualification step.

Qualification Step	Main Parameters to be Controlled
Part build process	Purge gas, deposition environment, build a plan, laser parameters such as spot size, laser power, laser travel speed, laser dwell time, preheat temperature, interpass temperature, layer thickness.
Proof parts	Assess the buildability using software simulation or other methods, Control equipment constraints.
Preliminary characterization	Usage of computational tools such as finite element, build test samples.

Qualification of the performance is the most critical quality control stand. This step simultaneously ensures that the raw material, equipment, parts, and process are in a manner that the final product fits the customer's requirements (Table 4). The qualification process may include both inspection and destructive or non-destructive test methods.

Table 4. The Main concerns in the qualification of final product.

Qualification Step	Parameters to Be Controlled
Non-destructive Testing	Visual inspection, X-ray, CT scan, ultrasonic, dimensional checks, hardness test.
Destructive testing	Grain size test, inclusion level, mechanical testing such as tensile, bend test, Charpy test, fatigue, weldability, corrosion tests.
Quality controls of the process	Statistical quality controls and sample tests, Comparison of data obtained from different quality control samples.

The types and number of required tests vary on component criticality. In the offshore oil and gas industry, the performance test types normally include metallurgical, mechanical, and corrosion tests. The test result variation can be compared within one build or between several builds.

5. Corrosion Concerns of Additively Manufactured 316L Material Grade

Big oil and gas companies such as General Electric (GE), Equinor, and Shell have previously shown early progress in using AM technology for the manufacturing of specific heat exchangers and gas turbine nozzles. However, before they can be able to widely use this technology for the production of other parts in offshore applications, they need to evaluate the incoming economic, health, safety, and environmental risks associated with using additively manufactured parts [35]. Additively manufactured parts previously had proven to have satisfactory mechanical performance for high-pressure applications [36]. Therefore, the mechanical strength of the additively manufactured parts, except for fatigue-related problems, is not a very challenging issue in the oil and gas industry. Instead, the main challenge is the risks incurred by corrosion mechanisms, as the corrosion performance of the additively processed materials is under question.

According to Lodhi et al. [37], in wrought stainless steel, most of the localized corrosion happens in MnS locations. In the additive manufacturing process, the manganese and sulfur elements lose the chance to produce inclusions in the form of MnS, because of the high cooling rate and the rapid solidification during the process. Therefore, due to the low MnS type inclusion content of the additively manufactured samples, these samples show a higher resistance to localized corrosion than the wrought counterparts.

The passive film at the surface of stainless-steel parts plays vital role in the corrosion resistance of the material. This passive film includes oxides and hydroxides of chromium and iron. Based on the electrochemical impedance spectroscopy study, the researchers showed that the passive film in AM 316L is richer in iron and chromium and is much denser, thicker, and has fewer defects than that of the wrought counterparts [37]—increasing the general corrosion resistance of the AM 316L steels.

It is well known that hydroxides prevent the penetration of anions such as Cl^- in chlorine-containing environments; AM 316L samples are also more prone to pitting corrosion. This finding is supported by other experiments [36,38] that report that the pitting corrosion increases in AM 316L samples due to the Cr/Mo segregation in the microstructure. However, several other investigations have reported different results about the pitting resistance of AM 316L material grade. According to this research, the reduction of MnS content in the microstructure of the AM samples enhances the passive film formation and reduces the pitting promotions [37,39,40].

Intergranular corrosion is the main problem in high-temperature applications, especially in the temperature range between 500–850 °C. In this mechanism, the secondary precipitates are formed at the grain boundaries, which leads to the production of chromium-free regions at the microstructure, and eventually causes intergranular corrosion. Chromium carbide deposition at the grain boundary is one of the key factors in assessing the rate of intergranular corrosion. SEM analysis by Laleh et al. [41] showed that the amount of chromium carbide deposits in the grain boundaries of AM 316L is substantially lower than that of the wrought stainless steels. Therefore, the intergranular corrosion resistance of the additively manufactured 316L samples is significantly better than its wrought counterparts [42].

The corrosion fatigue behavior of AM 316L steels is affected by two factors (1) internal porosity and (2) surface roughness. According to the limited studies regarding the corrosion behavior of AM 316L steels, in low applied loads, fatigue starts from the surface of the sample. However, in high applied loads, fatigue starts from internal defects such as porosity locations in additively manufactured samples.

Table 5 compares the corrosion behavior of the additively manufactured and wrought 316L material grade. As it can be understood from the above discussion, the corrosion performance of the additively manufactured components is not fully understood, and this is a research gap that should be filled before any qualification attempt.

Table 5. Comparison of the corrosion susceptibility of additively manufactured 316L and wrought 316L material grade.

Corrosion Mechanism	Susceptibility of AM 316L in Comparison to Wrought 316L
General corrosion	Improved
Pitting	Contradictory reports
CLSCC	Not reported
Localized corrosion	Improved
Intergranular corrosion	Improved
Hydrogen-induced cracking (HIC)/Sulfide stress cracking (SSC)	Not reported
CO_2 corrosion	Not reported
Fatigue resistance	Decreased

6. Risk-Based Qualification of AM Process

Additive technology is in its growing stage, and variability in AM machines and equipment can lead to inconsistency in the microstructure, the existence of defects, and uncertainties in the mechanical and corrosion performance of the finished parts. While additively manufactured components may have different applications, the criticality of active damage mechanisms in different operating conditions can be different. For example, porosity type defects are critical for sour service applications and in conditions where the fatigue mechanism is active, such as in low-diameter piping branches under vibrations. Therefore, it is a worthy and economical method to set the scope of the qualification activities based on the severity of the actual operating condition. A risk-based qualification process helps to reduce the qualification costs by concentrating on the most critical damage types and less on low-risk conditions [43].

Qualification activities aim to reduce the risk of the presence of defects in the material and ensure that the components are produced based on the customer's requirements. A risk-based qualification process defines the scope of the inspection, types of real-time monitoring, control techniques, and also the material inspection methods used based on the risk of the active damage mechanisms. In this process, risk is defined as the product of the probability of an error (POE) and the consequence of an error (COE).

Figure 3 shows different steps in the risk-based qualification process. As is clear, the main steps include damage mechanism identification and the development of an inspection and test plan (ITP). The risk level of the active damage mechanism plays a vital role in the definition of the inspection and test plan for the component. In this process for high-risk categories, ITPs are developed using advanced test methods and considering the extended scope of inspections. However, less expensive inspection and test methods are considered for low-risk damage categories. For this reason, the inspection and test methods can be categorized into three levels, such as the example provided in Table 6. In this example, category A relates to inspection and test methods with the capability to identify 80% of possible errors and defects, while category B methods include inspection and test methods capable of identifying errors and defects with certainty between 60 and 80%, and finally, category C include the methods which are able to identify errors and defects with certainty between 40 and 60%. The purpose of the risk-based qualification process is to reduce the risk of the presence of unacceptable defects in a component. According to Figure 3, at the end of the qualification process, the appraiser would assess if the risks are in a tolerable range or not. If the answer is no, it is necessary to review all steps and make corrections where required until the component achieves an acceptable performance. In this procedure, all steps except the execution of the qualification plan can be performed offline and are based on available technical data. The goal of the qualification plan is to keep the scope and number of tests as minimal as possible. While the scope and number of tests affect the cost of the qualification job, it is the type and method of the inspection that dictates the number of inspection stands in the execution stage. The latter affects the cost of the qualification process even more. The risk-based procedure helps to plan the optimal inspection method. Generally, the inspection and test methods are chosen based on engineering practices and considering previous experiences. There is no guarantee the initially suggested ITP will work well, therefore, for oil and gas companies to assure that the suggested ITPs work well, they use performance assessment tests on manufactured components. This step checks whether the subscribed test type and scope are sufficient and suitable for the requested quality or not. The performance assessment tests normally are performed in a laboratory or real industry.

Table 6. Example of categorizing inspection and test methods for risk-based qualification procedure.

Inspection and Test Category	Risk Category	Damage Mechanism	Inspection and Test Methods	Scope
A	High	SSC/HIC Fatigue	Mechanical tests, X-ray diffraction of powder, Digital imaging and sieve analysis of the powder morphology, SEM study of the final microstructure, SSC/HIC tests, CT-scan	3 samples per heat
B	Medium	SSC/HIC Fatigue	Mechanical tests, X-ray diffraction of powder, Sieve analysis and laser diffraction for powder morphology, SEM study of the final microstructure, SSC/HIC tests.	1 sample per heat
C	Low	SSC/HIC Fatigue	Mechanical tests, Energy dispersive X-Ray spectroscopy of powder, optical microscopy study of the final microstructure.	Random from every 10 heat

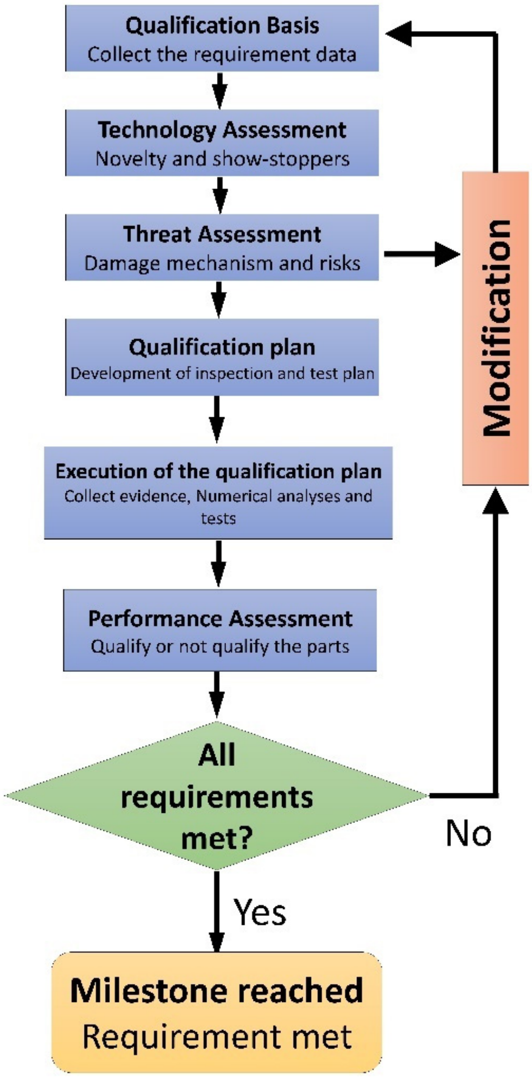

Figure 3. Risk-based qualification process.

7. Results and Discussion

This study shows how the risk-based qualification approach can be implemented into the qualification of additively manufactured parts. For this aim, an example qualification for a nozzle component fabricated using AM is presented. Previously, this type of nozzles is used for downhole cleanouts of oil and gas wellbores using the combination of traditional machining and an extra wire cut working. Before the introduction of AM, the only alternative was to fabricate these components by assembling several smaller parts. However, Norway's EnergyX recently succeeded in producing this type of nozzle using AM, which helps enhancement of the integrity of the nozzle and also reduces the costs [44].

Figure 4 shows the nozzle assembled to the intended location in pipe work. This type of nozzle can be made of carbon steel, stainless steel or Inconel grades. However, for the aim of this work, the nozzle is considered for application in mild sour service and based on engineering best practices, the stainless steel nozzle is a good choice for this type of fluid service. Table 7 indicates a list of active damage mechanisms of additively manufactured stainless steel nozzles in downhole applications. As is obvious from Table 7, the additively manufactured components may have lower fatigue strength than the wrought stainless steel and therefore, the additively manufactured nozzle should be examined with a fatigue test before the application. This type of inspection may not be required for wrought components.

Figure 4. Additively manufactured Inconel 718 nozzle component [44].

Table 7. Active damage mechanisms of the stainless-steel nozzle in downhole applications.

Damage Mechanism	Risk Level	Justification
Metal Loss	low	The material is resistant to general corrosion mechanisms in this operating condition
Cracking	medium	The component is assumed to be exposed to chloride-containing fluids, mists, or solids; also, the temperature is in the susceptible range for external chloride stress corrosion cracking (CLSCC).
Metallurgical	low	In this operating temperature, metallurgical changes are not expected.
External corrosion	low	The only external concern is external cracking
Fatigue due to Manufacturing defects	High	The chance of the presence of lack of fusion, residual stress, and surface defects remaining from the manufacturing process is high. These parameters increase the risk of fatigue due to the fluid-induced vibrations.

Table 8 indicates the results of the risk-based qualification process for this additively manufactured stainless steel nozzle. In this qualification process, a three-level risk matrix (Figure 5) is used and inspection plans are categorized into three classes, including A, B, and C. The class "A" obtains more accurate inspection but is costly. Then this class should be used for the inspection of high-risk components. The risk of components is identified based on Figure 5.

According to the "scope" column in Table 6, for high-risk components, the number of required tests is also high. A high number of tests increases the confidence in the procedure; however, in a mean time it increases the inspection costs. In addition, according to this table, there is no need to use costly methods such as SSC/HIC tests and CT-scan for low-risk components such as components used in the vent section of the plant.

As is clear from Table 8, if an AM system is used for the production of this stainless-steel nozzle component for downhole cleanout applications, the chemical and metallurgical characteristics of the feed powder, process parameters, metallurgical, and corrosion tests of the final samples, non-destructive inspection of the produced samples are the most quality-affecting parameters. It means that these parameters should be controlled using much stricter measures, e.g., by using advanced NDE methods for all samples. However, for qualification stands with the medium risk category, the medium level evaluation methods for two-thirds of the samples are suggested. Random inspection using less developed methods for low-risk qualification items can be acceptable.

Table 8. Result of risk assessment for qualification of additively manufactured stainless steel nozzle for downhole application, (red: high risk, yellow: medium risk, green: low risk levels).

Qualification Stand	Qualification Parameter	POE	Consequence on Final Product	COE in Wellbore Application	Risk Level	Main Concerns and Methods
Technology Assessment	Process and technique assessment	L	Unqualified products	High	M	Full documentation
	Repeatability	M	Dimensional problems	Medium	M	-
Pre-processing qualification	3D model formanufacturing and Integrity of software	L	Incorrect manufacturing	Low	L	Mesh size to be controlled and meshing conversion errors should be corrected. Verification of build layout with orientation, support structures & test specimens.
	Preliminary characterization and proof parts	L	Incorrect manufacturing	Low	L	pre-manufacturing procedure summary
Qualification of Raw Material	Chemical and metallurgical	M	Weak against Crack and corrosion	High	H	- X-ray diffraction - X-ray photoelectron spectroscopy - Auger electron spectroscopy - energy dispersive X-Ray spectroscopy
	Morphological and Geometrical	M	Weak Performance	Medium	M	- sieve analysis - microscopy - laser diffraction - digital imaging
	Mechanical and Physical	L	Weak against Cracks and corrosion	High	M	Moisture content, flow rate, bulk density, compressibility, green strength.
Manufacturing Procedure Qualification	Process parameters	M	Weak performance	High	H	Heat input, beam power, beam diameter, and intensity, beam scan pattern (spiral, meander, etc.), bead cooling rate, powder preheat, in situ AM process monitoring, In situ process monitoring of melt pool.
Post-processing qualification	Heat Treatment	L	Weak against cracks and corrosion	High	M	Temperature and time
	Surface correction	L	Weak against fatigue	Medium	L	Surface roughness, etc.
	Mechanical Features	L	Low strength	Medium	L	Hardness, fracture toughness, cellular structure, fatigue, strength
Qualification of final product	Metallurgical and corrosion	M	Weak against cracks and corrosion	High	H	- potentiodynamic polarization - cyclic potentiodynamic polarization (CPP) - static immersion test - HIC/SSC
	Mechanical Integrity	H	Defective component	High	H	- high resolution of porosity in 3D-surface roughness, morphology - density of particles - non-destructive Evaluations - fatigue test

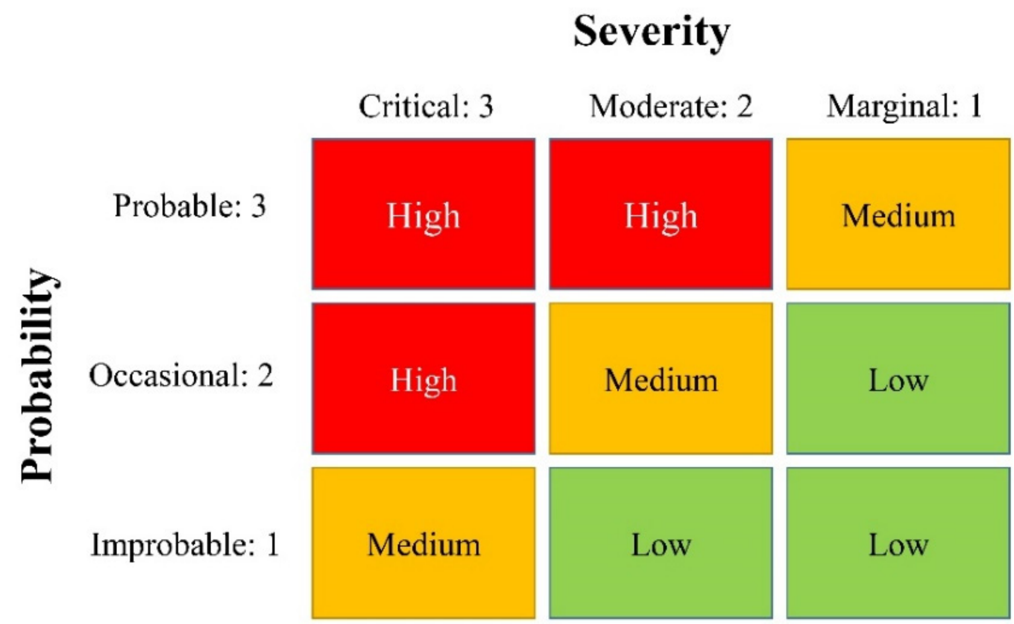

Figure 5. Three-level risk matrix.

8. Conclusions

- Qualification elements of the additive manufacturing process are discussed in detail and risk-based qualification procedure for qualifying additively manufactured components for use in the oil and gas industry are suggested. The risk level of the inspection stands is identified. The results can help to determine the optimal scope and domain of inspection methods during the development of an inspection and test plan. The literature review showed that there was a research gap within the sour corrosion performance of the additively manufactured parts, which restricts the qualification of these materials for offshore oil and gas applications. According to the risk-based qualification process, the chemical and metallurgical characteristics of the feed powder, process parameters, metallurgical and corrosion tests of the final samples, non-destructive inspection of the produced samples were the most critical qualification stands for offshore applications and shall be controlled strictly.
- There are process-induced risk drivers in AM, such as lack of fusion, and residual stress and porosity, which are not common in wrought components. Then, contrary to wrought stainless steel parts that only their welded regions are vulnerable to fatigue failures, in additively manufactured components, the fatigue test of the base metal may also be required in components exposed to vibrations.

Author Contributions: B.A.: Conceptualization, R.M.C.R.: Supervision. M.E.: Writing—Reviewing and Editing. M.A.: Data curation. H.R.: Writing—Original draft preparation. M.N.E.: Methodology. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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