DNV·GL

CLASS GUIDELINE

DNVGL-CG-0197 Edition November 2017

Additive manufacturing - qualification and certification process for materials and components

DNV GL AS

FOREWORD

DNV GL class guidelines contain methods, technical requirements, principles and acceptance criteria related to classed objects as referred to from the rules.

Any comments may be sent by e-mail to *rules@dnvgl.com*

CHANGES – CURRENT

This is a new document.

CONTENTS

SECTION 1 GENERAL

1 Introduction

1.1 Objective

The purpose of this guideline is to support the introduction and use of additive manufacturing (AM) technologies as an alternative method to produce materials, parts or components that are subject to approval or verification in accordance with DNV GL rules and/or other applicable standards used by the Society.

> **Guidance note:**
>
> AM is a term used to cover a broad range of manufacturing processes (also known as 3D printing) that involve sequential-layer material addition throughout a 3D work envelope under automated control.
>
> ---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

1.2 Scope

This class guideline provides a framework for approval and certification of materials, products and components made by additive manufacturing (AM) through a systematic qualification approach.

Interfaces between AM technologies and conventional technologies already covered by existing rules and standards may be covered by this class guideline based on a case-by-case agreement with the Society.

1.3 Application

This document is applicable to stakeholders in the maritime industry, e.g. manufacturers and sub-suppliers of materials, parts and components, service suppliers and end users adopting AM technologies. The guidelines may be applied for:

- approval of pre-materials, materials, parts and components made by the use of additive manufacturing process
- approval of AM related services
- specification of part-building requirements for end users.

It is applicable for materials, parts and components made by any AM processing route that may be defined as one of the emerging AM technologies or concepts, but not covered by existing conventional manufacturing or fabrication routes. Requirements for the qualification of manufacturers shall be considered in each case. This consideration shall take into account the complexity and criticality of the product to be supplied, manufacturer’s previous experience, and these guidelines.

1.4 Structure

This document is structured into three sections:

Section 1:

- introductory section where the objective, scope and other general details are presented.

Section 2:

- contains a brief introduction to AM technologies and discusses general principles of additive manufacturing processes, important process parameters and variables. This section is mainly for reference purposes.

Section 3:

- provides guidance to the qualification process for additively manufactured materials and components, AM qualification and certification work process and various services offered by DNV GL.
  See App.C.

Appendices:

— includes supplementing information, such as principles and steps of the technology qualification process, and a list of various test methods relevant for AM materials, parts and components.

1.5 Relationship to other rules, codes and standards

General requirements for manufacturing and fabrication of materials and components are given in DNVGL-RU-SHIP Pt.2 Ch.1 and DNVGL-OS-B101 Ch.1, specific requirements for manufacturing of materials are given in DNVGL-RU-SHIP Pt.2 Ch.2 and DNVGL-OS-B101 Ch.2, and specific requirements related to welding and fabrication are given in DNVGL-RU-SHIP Pt.2 Ch.4 and DNVGL-OS-C401. Additional requirements are provided in other parts of the rules, DNVGL-RU-SHIP Pt.3 to DNVGL-RU-SHIP Pt.7 and other relevant DNV GL offshore standards.

For generic qualification procedures for new technology and service specifications, see DNVGL-RP-A203 and DNVGL-DSS-401.These guidelines provides a specific qualification procedure for how to utilize DNVGL-RP-A203 for qualification of AM technologies.

See App.C.

1.6 Definitions and abbreviations

Table 1 Definitions

Term	*Definition*
3D printing	the fabrication of objects through the deposition of a material using a print head, nozzle, or other printer technologies
additive manufacturing	a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication
3D scanning	a method of acquiring the shape and size of an object as a 3-dimensional representation by recording x,y,z coordinates on the object’s surface and,by use of software, the collection of points is converted into digital data
3D printer	a machine used for 3D printing
directed energy deposition	an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited
powder bed fusion	an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed
direct metal laser sintering	a powder bed fusion process used to make metal parts directly from metal powders without intermediate “green” or “brown” parts; term denotes metal-based laser sintering systems from EOS GmbH – Electro Optical Systems
technology qualification plan	the qualification activities specified with the purpose of generating qualification evidence and the logical dependencies between the individual pieces of qualification evidence
technology qualification program	the framework in which the technology qualification process is executed as detailed in Ch.4
verification	confirmation by examination and provision of objective evidence that specified requirements have been fulfilled (ISO 8402:1994)

Term	*Definition*
reliability	the ability of an item to perform a required function under given conditions for a given time interval or at a specified condition. In quantitative terms, it is one (1) minus the failure probability
technology qualification	technology qualification is the process of providing the evidence that the technology will function within specified limits with an acceptable level of confidence
milestone	a point in the technology qualification process that signifies an agreed stage has been achieved which may be used to trigger other events such as recognition, reward and further investment
decision gate	a point in time where a decision is taken on whether to continue a technology development process or a project development

Table 2 Abbreviations

Abbreviation	*Description*
AM	additive manufacturing
CAD	computer-aided design
CAM	computer-aided manufacturing
CNC	computer numerical control
DG	decision gate
DMLS	direct metal laser sintering
DNV GL	DNV GL AS
LS	laser sintering
SLS	selective laser sintering
TQ	technology qualification
TRL	technology readiness level

1.7 References

/1/ DNVGL-RP-A203 *Qualification Procedures for New Technology*

/2/ DNV-DSS-401 *Technology Qualification Management*

/3/ DNVGL-CP-0337 *General description of services for certification of materials and components*

/4/ DNVGL-RU-SHIP DNV GL rules for classification: Ships (RU-SHIP)

/5/ ISO/TC 261 and ASTM F42, *Joint Plan for Additive Manufacturing Standards Development*

/6/ SAE AMS4999A, *Titanium Alloy Direct Deposited Products Ti-6Al-4V Annealed*

/7/ DNVGL-CP-0287 *Hybrid laser-arc welding*

/8/ ISO / ASTM52900 - 15, *Standard Terminology for Additive Manufacturing – General Principles – Terminology*

/9/ DNVGL-OS-B101 *DNV GL offshore standard, Metallic materials*

/10/ DNVGL-OS-C401 *DNV GL offshore standard, Fabrication and testing of offshore structures*

/11/ DNVGL-CP-0351 *Manufacture of heat treated products - heat treatment workshop*

/12/ DNVGL-CP-0346 *DNV GL approval of manufacturer scheme*

/13/ DNVGL-CP-0338 *DNV GL type approval scheme*

SECTION 2 ADDITIVE MANUFACTURING

1 Introduction

This section provides information regarding additive manufacturing technology in general and an overview of various AM processes. Further it discusses important aspects of the AM product life cycle, explaining various elements related to the qualification and certification process. This section does not contain any requirements, but serves as a reference section for preparing documentation during the qualification and certification process (see Sec.3 Figure 2).

1.1 Additive manufacturing

Additive manufacturing (AM), also referred to as 3D printing, is a common name for technologies where an object is manufactured layer by layer.

Additive manufacturing enables the building of three-dimensional, solid objects from digital models, and thus the realisation of complex parts. This in contrast with many traditional manufacturing methods, (subtractive manufacturing), where the final parts are machined out from a pre-made form. In some cases, additive manufacturing can be considered as a supplement to conventional production technologies. In other cases, it is the only means through which complex products can be fabricated.

The range of available materials currently printable is constantly and rapidly expanding. Whereas additive manufacturing was originally used for prototyping, it is now more and more applied to manufacturing end-products.

A further distinguishing feature of AM is its distributed nature. On-site manufacturing for maintenance becomes an important application of AM. While traditional manufacturing mostly takes place at a centralised facility, with the resulting parts distributed to end users, AM has the potential for manufacture implementation at the point-of-use. This enables innovations in manufacturing value chains, many of which are still being realised.

Since AM technologies are still immature, there is a lack of relevant standards, guidelines and recommendations for stakeholders to rely on. The immature nature of AM technologies causes uncertainties and increased risk exposure for involved stakeholders. Hence, qualification and certification becomes unnecessarily complicated and time consuming for all involved parties.

DNV GL’s technology qualification methodology provides a systematic way to manage the uncertainties related to implementation of new technology in cases where fitness for purpose cannot solely be relied on by demonstrating compliance with relevant standards, guidelines and recommendations. The process makes it possible to identify and analyse the risks associated with the new technology, and provide evidence that it is suitable for its intended use. It can therefore play an important role in increasing the confidence in new AM technologies and facilitating a faster, more efficient and more reliable deployment of AM materials and components to maritime applications. See App.C.

1.2 Additive manufacturing in comparison with conventional manufacturing

Compared to conventional manufacturing, the general advantages of AM are the capabilities in design and development of products. The ability to produce highly complex parts without tools, a decrease of production costs is possible. Since there is no need to produce a large amount of an individual part to refinance the tools, as for traditional manufacturing, AM is well suited for low volume production. Hence, affordable and high complexity individual products can be manufactured.

Due to the differences in AM compared to conventional manufacturing, the follow-up processes for manufactured product quality are different. In order to provide a basis for future certification activities for the additive manufacturing (AM) technology, it is important to collect and analyse information related to established production steps for additive manufactured metal parts, as that act as the largest contributors to product quality. A life cycle analysis of AM compared to conventional manufactured parts is required. However, it is important to note that a holistic analysis of AM products covering the product life cycle is lacking in the current literature.

Despite it's limitations, an increasing number of manufacturers are using AM to benefit from possibilities like complexity-for-free manufacturing. In traditional manufacturing there is a direct correlation between complexity and manufacturing costs. For AM, there’s in principle no limitation to the complexity of geometry, without the need to produce any tools (e.g. forming tools). Consequently, most restrictions of design for manufacture and assembly are not valid for AM. Designs intended for traditional manufacturing are often heavily limited by high costs in construction and tool-making. The greater freedom of design via AM makes it possible to combine an assembly of parts into one part and therefore, to reduce the required assembly work and costs. In addition, no compromises regarding the assembly capabilities are necessary.

Table 1 Comparison of typical characteristics of additive manufacturing and conventional manufacturing routes

Additive manufacturing route	*Conventional manufacturing route*
— low production volumes — high material cost — high machining cost — low capital investment — low logistics costs — low transportation costs — rapid prototyping	— large production volumes — low material costs — easily processed/machined materials — centralized manufacturing

AM makes it possible to replace several conventionally manufactured and assembled parts with one part. This allows for an integration of functions from different parts, which may result in better performance and less maintenance. Even where requirements to movability of a part in relation to standing parts exists, e.g. ball and socket joint, the production with AM can be completed as a single, monolithic structure. The applied design rules for conventionally manufactured parts are not applicable to parts produced by AM, hence, design guides for AM products must be reconsidered. In addition to the freedom of design, reduced assembly cost may contribute to lowering the total production costs further.

The targeted design of a relieved or decreased assembly may result in a much higher reduction of the production costs than the construction compared to parts designed for conventional manufacturing. A reduced number of parts provides other advantages,, like fewer parts to be sourced, labelled and evaluated. This also reduces the number of spare parts to be stocked. Since there is no need of tooling for production of spare parts, it is unnecessary to hold legacy tooling in storage. As a consequence, AM is the simple way to produce complex geometric structures. The complexity of the production and the whole management decreases and therefore savings in the entire business chain may be achieved.

1.3 Additive manufacturing adoption in maritime

Classification rules and standards ensure the safety, reliability, and quality of processes and products. Rules and standards also provide a foundation for creating products that conform to certain specifications and are compatible with products provided by different suppliers seeking the same quality, performance and interchangeability.

Because there are currently only a handful of additive manufacturing standards, companies conduct their own testing to ensure integrity of the equipment, processes and products. Costly and time-consuming testing deters wider application of additive manufacturing, underscoring the need to develop standards from design to part build to operation.

Hence one of the most serious hurdles to the broad adoption of additive manufacturing of materials in regulatory industry regimes such as ship and offshore classification is the qualification and certification guidelines for additively manufactured parts.

Some of the challenges related to qualification and certification of AM process and components are:

- There is a lack of information related to material properties, and we have much less experience and scientific knowledge of AM processes than that of conventional manufacturing.

- Risk assessment based on statistics of large-volume history data does not apply to AM production as for conventional manufacturing.
- AM process has a more disintegrated processing route compared to conventional manufacturing. Hence a global traceability solution, enclosing multiple AM and supply chain locations will be needed more than ever.
- Secrecy about technology and software/algorithm sources is an obstacle. Since software plays an important role in product quality it is a subject of concern for certification.
- Directionality and heterogeneity of AM products can bring challenges for certification and testing.
- Lack of product reproducibility and uncertainty of quality control still exist.

1.4 DNV GL's approach for additive manufacturing adoption

Despite the challenges to further adoption, many experts believe additive manufacturing will significantly change certain production and distribution activities. To meet the full potential of AM, especially for safety critical components (e.g., rotating parts, fracture-critical parts, etc.), qualification and certification processes are required.

It is very important that industry finds alternatives to conventional qualification methods; these are likely based upon validated models, probabilistic methods, and part similarities. Part-by-part certification is costly, time consuming, and antithetical to achieving the industry’s vision of producing and using AM parts on demand. At the same time, it is important to establish guidelines that may create a framework to approval and certification of additively manufactured components for adoption in maritime sector.

Hence DNV GL is taking initiative in this new area by bringing together results from research and development alongside real-world additive manufacturing practices to create new industry product certification guidelines – paving the way for more widespread adoption of the additive manufacturing technology.

2 Principles and overview of additive manufacturing processes

2.1 Additive shaping of materials

Additive manufacturing is a suite of emerging technologies that fabricates three-dimensional objects directly from digital models through an additive process. The functionality of an additively manufactured object is derived from the combination of the object’s geometry and properties. In order to achieve this combination, a manufacturing process is made up of a series of operations and sub-processes that brings the shape of the intended geometry to a material capable of processing the desired properties. Additive manufacturing technology applies the additive shaping principle and thereby builds physical 3D geometries by successive addition of material. ‘Addition of material’ means that units of material feedstock are brought together and joined, most commonly layer by layer to build a part. The determining factor for each process is in the technique used for adding the materials. This determines, as an example, what types of materials are possible in the process, as different materials have different principles of fusion or adhesion. Basically, for additive manufacturing processing, the product's fundamental properties are determined by

a) material type (polymer, metal, ceramic or composite, etc.)
b) principle applied for fusion or bonding (melting, curing, sintering, etc.)
c) feedstock used for adding material (liquid, powder, wire, filament, sheet, etc.)
d) how the material is shaped (type of machine, machine architecture, etc.)

The process of successively adding material to build a part makes the properties of the material in this part highly dependent on the machine type and the processing and post processing parameters in the additive operation. Therefore, it is not possible to accurately predict these material properties without coupling them to a specific type of machine and process parameters.

A layered approach to the additive shaping of parts may also cause directional dependence in the material properties. Therefore, material properties in an AM part may be dependent on the part's orientation and position in the build space during processing.

2.2 Additive manufacturing processing principles

There are numerous ways in which units of pre-material can be joined together to form a part. Different types of materials are being held together by different types of atomic bonds; metallic materials are typically held together by metallic bonds, polymer molecules typically by covalent bonds and composite materials by any combination of the above-mentioned types. The type of bonding provides the most fundamental conditions for how that type of material can be joined in an additive process. Besides the type of material, the joining operation is so dependent on in which shape the material is delivered to the system, and how it is distributed. For additive manufacturing process, the feed stock, that bulk raw material that is fed into the process, can typically come in the form of powder, filament, sheet, molten metal and for polymers also in the shape of un-cured liquid material. Dependent on the shape, the feed stock may then be distributed layer by layer in powder bed, deposited by nozzle, applied as layers in a sheet stack, deposited through a printed head, or applied as a liquid, paste or slurry in a vat. In respect to the great possibilities for variation in different types of materials, different types of feed stock and means of distribution of the feed stock, there is large number of possible principles that could be used for additive manufacturing processes.

2.3 Main processing steps in additive manufacturing

Additive manufacturing is in general the opposite of subtractive manufacturing, where material is removed to reach the desired shape. In AM, 3D parts are built up in successive layers of material under computer control. Additive manufacturing begins with computer-aided design (CAD) modelling software that takes a series of digital images of a design or object and sends descriptions of them to a professional-grade industrial machine. The machine uses the descriptions as blueprints to create the item by adding material layer-upon-layer. Layers, which are measured in microns of thickness, are added by the hundreds or thousands until a three-dimensional object emerges. Raw materials may be in the form of a liquid, powder or sheet, and are typically plastics and other polymers, metals or ceramics. After part manufacturing, post processing operations are needed to improve material performance.

A number of additive manufacturing processes differ from each other in the materials and methods which they employ to scan and form layers. Major processes include material extrusion, material jetting, binder jetting, sheet lamination, vat photopolymerization, powder bed fusion and directed energy deposition. Some of these melts or soften material to produce the layers, while others solidify liquid materials using different sophisticated technologies.

Figure 1 summarises the important processing steps in AM.

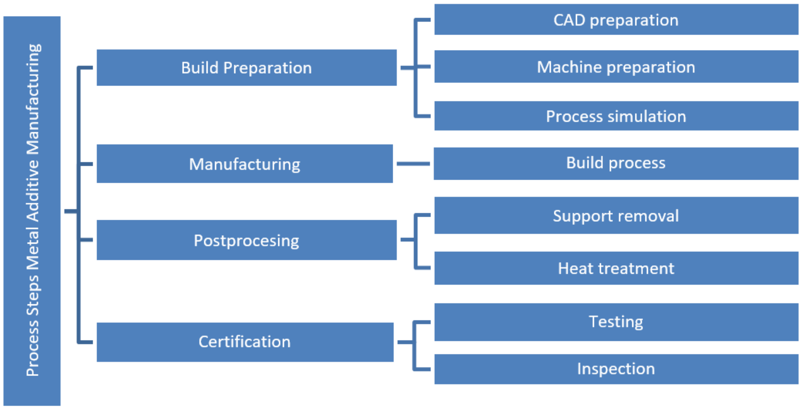


Figure 1 Rough production model for materials/products produced through additive manufacturing route

2.4 Overview of additive manufacturing process variables

Normally a series of operations and sub-processes are required to manufacture a finished product and achieve the intended combination of geometrical shape and desired properties. In additive manufacturing, there is a distinction between operations that are indispensable parts of the additive process and the product- and application dependent pre- and post processing operations. In order to apply the appropriate standards, this distinction is important when additive manufacturing is applied within an industrial manufacturing system.

Table 2 Overview of additive manufacturing processing variables based on process variables

Variable type	*Typical variables for metallic materials*	*Typical variables for polymers*
State of fusion	Liquid, solid, solid + liquid	Thermal reaction bonding, chemical reaction bonding
Material feed stock	Filament/wire, powder, sheet	Filament, powder, liquid, sheet
Material distribution	Deposition nozzle, powder bed, sheet stack	Deposition nozzle, print head, powder bed, sheet stack
Type of AM process	Selective deposition/fusion of a material to substrate, fusion of stacked sheets	Extrusion of molten material, multi-jet material printing, selective fusion, reactive curing, photopolymer curing, fusion of stacked sheets
Source of fusion	Electron beam, laser, ultrasound	
Process category	Directed energy deposition, powder bed fusion, sheet lamination	Material extrusion, material jetting, powder bed fusion, binder jetting, vat photopolymerization, sheet lamination

2.5 Role of various influential parameters in additive manufacturing process

Various process parameters influence the final quality of AM part. Various influential parameters of the typical AM process chain at different stages of AM part production are summarized in Figure 2.

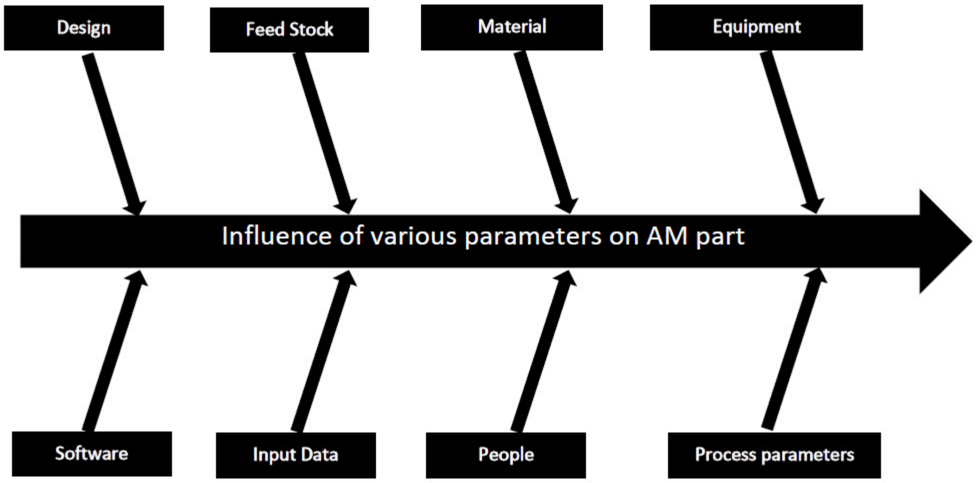
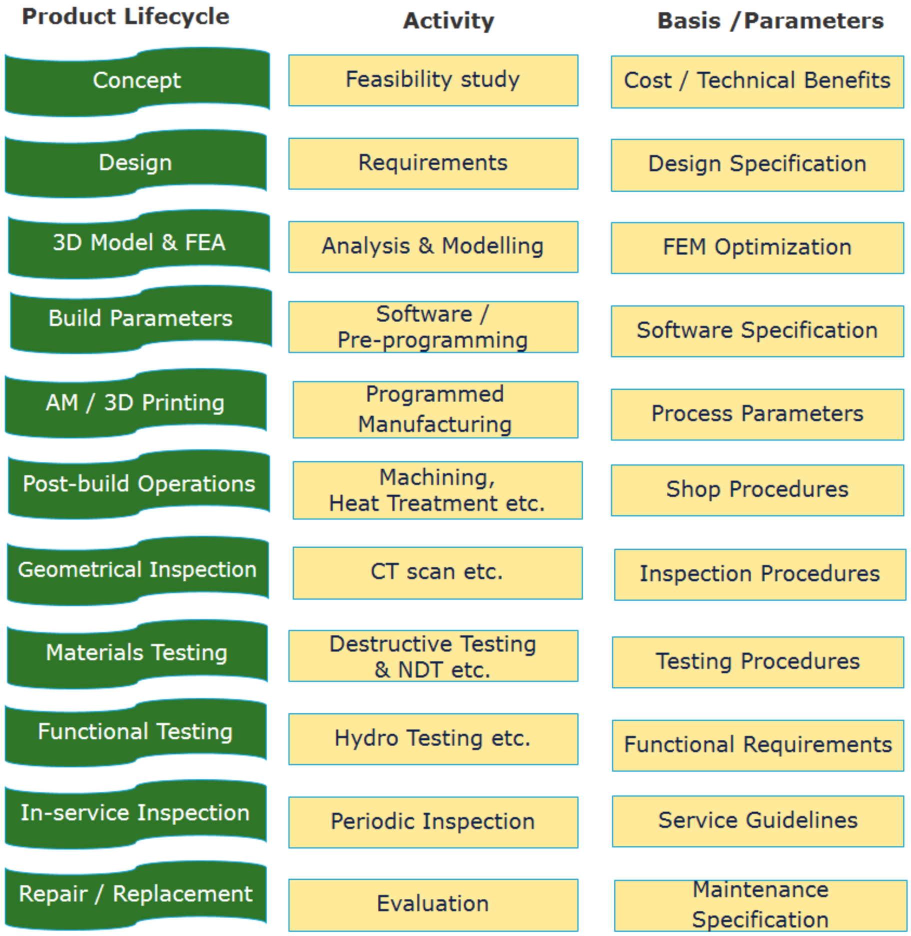


Figure 2 Aspects of the process chain and their influence on parameters of additive manufacturing process.

3 Additive manufacturing process description and variables

3.1 Overview of additive manufacturing product and process life cycle

To provide a basis for future certification activities for the additive manufacturing (AM) technology, a life cycle analysis of the additive manufactured parts is needed to be performed on the additive manufactured products . Hence, it is important to collect and analyse the information regarding established/emerging production steps for additive manufactured metal parts that act as the largest contributors to product quality. Typical life cycle for materials/products produced through additive manufacturing route is shown in Figure 3.



Product Lifecycle	Activity	Basis /Parameters
Concept	Feasibility study	Cost / Technical Benefits
Design	Requirements	Design Specification
3D Model & FEA	Analysis & Modelling	FEM Optimization
Build Parameters	Software / Pre-programming	Software Specification
AM / 3D Printing	Programmed Manufacturing	Process Parameters
Post-build Operations	Machining, Heat Treatment etc.	Shop Procedures
Geometrical Inspection	CT scan etc.	Inspection Procedures
Materials Testing	Destructive Testing & NDT etc.	Testing Procedures
Functional Testing	Hydro Testing etc.	Functional Requirements
In-service Inspection	Periodic Inspection	Service Guidelines
Repair / Replacement	Evaluation	Maintenance Specification

Figure 3 Typical lifecycle for materials/products produced through additive manufacturing route

3.2 Principle processes for metal additive manufacturing

There are multiple processes developed for additive manufacturing. The two main parameters of any metal AM process are type of input raw material and energy source used to form the part. Input raw material can be used in the form of metal powder or wire, and laser/electron beam or arc can be used as energy source.

Metal AM processes can be broadly classified into two major groups, – powder bed fusion based technologies (PBF) and directed energy deposition (DED) based technologies. Both of these technologies can be further classified based on the type of energy source used. In PBF based technologies, thermal energy selectively fuses regions of powder bed. Selective laser sintering/melting (SLS/SLM), laser fusing and electron beam melting (EBM) are main representative processes of PBF based technologies. In DED based technologies, focused thermal energy is used to fuse materials (powder or wire form) by melting as they are being deposited. Laser engineered net shaping (LENS), direct metal deposition (DMD), electron beam free form fabrication (EBFFF) and arc based AM are some of the popular DED based technologies.

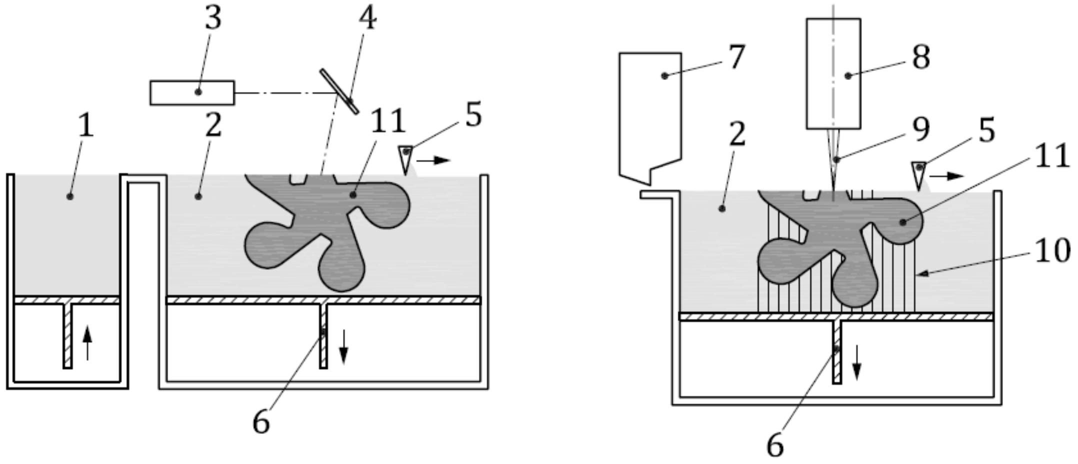
3.2.1 Powder bed fusion

The definition of powder bed fusion according to ISO 17296-1 is an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed. Powder materials could be used with, or without, fillers and binders depending on the specific process. Binding mechanism is thermal reaction binding. Source of activation is thermal energy which is typically transferred from laser, electron beam, and/or infrared lamps. Support structure and build substrate is normally required for the processing of metallic feedstock. The powder bed is in inert atmosphere or partial vacuum to provide shielding of the molten metal. An energy source (laser or electron beam) is used to scan each layer of the already spread powder to selectively melt the material per the part cross section obtained from the digital part model. When one layer has been scanned, the piston of building chamber goes downward and the piston of the powder chamber goes upward by defined layer thickness. Coating mechanism or roller deposits powder across build chamber which is again scanned by the energy source. This cycle is repeated layer by layer, until the complete part is formed. The end result of this process is powder cake and the part is not visible until excess powder is removed. Build time required to complete a part in PBF based processes is more as compared to DED technologies but, higher complexity and better surface finish can be achieved which requires minimum post-processing. Several parts can be built together so that build chamber can be fully utilized. Schematic of the PBF technology is shown in Figure 4.

These processes inherently require support (of same material as part) to avoid collapse of molten materials in case of overhanging surfaces, dissipate heat and prevent distortions. Supports can be generated and modified as per part requirement during pre-processing phase and the same has to be removed by mechanical treatment during post-processing phase. After support removal, part may undergo postprocessing treatments like shot peening, polishing, machining and heat treatment depending on the requirement. Some critical components may even require hot isostatic pressing (HIP) to ensure part density.

Selective laser sintering (SLS) or direct metal laser sintering (DMLS), selective laser melting (SLM) and laser cusing are some of the popular PBF based technologies which use laser as energy source whereas electron beam melting (EBM) is PBF based technology which uses electron beam as energy source.

As compared to the SLM system, the EBM has higher build rates (up to 80cm^3/hr because of the high energy density and high scanning speeds) but inferior dimensional and surface finish qualities. In both the SLM/EBM process, because of rapid heating and cooling of the powder layer, residual stresses are developed. In EBM, high build chamber temperature (typically 700-900 °C) is maintained by preheating the powder bed layer. This preheating reduces the thermal gradient in the powder bed and the scanned layer which reduces residual stresses in the part and eliminates post heat treatment required. Preheating also holds powder particles together which can act as supports for overhanging structural members. So, supports required in the EBM are only for heat conduction and not for structural support. This reduces the number of supports required and allows manufacturing of more complex geometries. Powder preheating feature is available in very few laser based systems where it is achieved by platform heating. In addition, entire EBM process takes place under vacuum since, it is necessary for the quality of the electron beam. Vacuum environment reduces thermal convection, thermal gradients and contamination and oxidation of parts like titanium alloys. In SLM, part manufacturing takes place under argon gas environment for reactive materials to avoid contamination and oxidation whereas non-reactive materials can be processed under nitrogen environment. So, it can be expected that EBM manufactured parts have lower oxygen content than SLM manufactured parts. In spite of having these advantages, EBM is not as popular as SLM because of its higher machine cost, low accuracy and non-availability of large build up volumes.



a) Laser based powder bed fusion

b) Electron beam powder bed fusion

Key

1 powder feeding system (in some cases powder container like 7)
2 powder material distributed in a powder bed
3 laser
4 tilted mirror with focus
5 powder spreading device
6 build platform

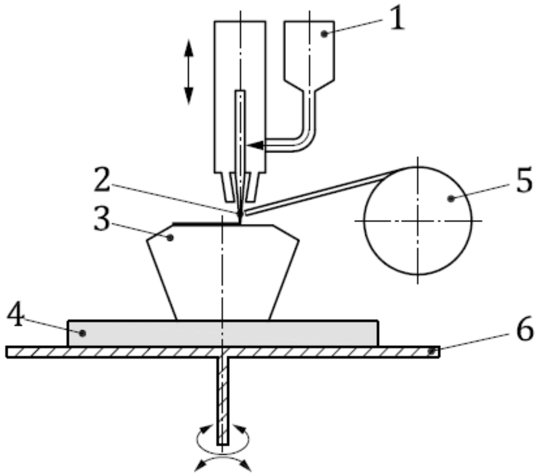
7 feedstock container
8 electron beam gun
9 focused electron beam
10 support structure
11 product

Figure 4 Schematic diagram of two types of powder bed fusion processes (see ISO 17296-2)

3.2.2 Directed energy deposition (DED)

Directed energy deposition (DED) processes enable the creation of parts by melting material as it is being deposited. Although this basic approach can work for polymers, ceramics, and metal matrix composites, it is predominantly used for metal powders or wire feedstock. Thus, this technology is often referred to as “metal deposition” technology. The definition of directed energy deposition according to ISO 17296-1 is an additive manufacturing process in which focussed thermal energy is used to fuse materials by melting they are being deposited. Powder or wire is the typical feed stock whereas binding mechanism is thermal reaction bonding. Sources of activation are laser, electron beam or plasma transferred arc. Machining, micro blasting, laser re-melting, grinding or polishing and heat treatment are typical secondary processing operations.

In direct laser deposition (DLD), powder is fed continuously into a molten pool on the surface of the substrate or previously deposited layer (see Figure 5). The molten pool is generated and maintained through an interaction with the laser beam and the powder injected into the pool forms another deposited layer after solidification. The substrate or deposited layer is melted to obtain good metallurgical bonding between the substrate and deposited layer or between successive deposited layers, in most cases to the depth of approximately one millimetre. Good powder consolidation is achieved by controlling the energy input at every location during the build. Energy input is a function of laser power, laser scanning speed and powder feed rate.



Key

1 powder hopper

2 directed energy beam, for example: laser, electron beam or plasma arc

3 product

4 substrate

5 wire (filament) coil

6 build table

NOTE 1 Multiple axis capability (typically 3-6 axis) is achieved by movement of nozzle and build table.

NOTE 2 Alternative material feeding systems, for example: powder fed in through the energy beam, powder fed in to the energy focal point,, of filament (wire) fed in to the energy focal point.

Figure 5 Schematic diagram of directed energy deposition processes (see ISO 17296-2)

Direct laser deposition can be used for producing new components, adding features to existing components, hybrid manufacturing or for repairing damage. It is possible to produce geometries that would not be possible using a single manufacturing process otherwise and therefore reduces the need for joints, which are often the weak point in a component. When adding secondary features to an existing component, DLD has the advantage of causing only a limited heat affected zone due to the small width of the laser melt pool.

Directed energy deposition (DED) systems have the following general collection of characteristics: ability to process large build volumes (>1000 mm^3), ability to process at relatively high deposition rates, use of articulated energy sources, efficient energy utilization (electron beam and arc plasma), strong energy coupling to feedstock (electron beam and arc plasma), feedstock delivered directly to the melt pool, ability to deposit directly onto existing components, and potential to change chemical composition within a build to produce functionally graded materials. Feedstock for DED is delivered to the melt pool in coordination with the energy source, and the deposition head (typically) indexes up from the build surface with each successive layer. DED has the ability to produce relatively large parts requiring minimal tooling and relatively little secondary processing. In addition, DED processes can be used to produce components with composition gradients, or hybrid structures consisting of multiple materials having different compositions and structures. DED processes are also commonly used for component repair and feature addition.

3.3 Design optimization and computer aided analysis

Each step of the AM production workflow is important to ensure hassle-free successful builds and high production rate. Judicious design, part orientation and appropriate supports types can make the difference between repeatable high production yield or costly time consuming mistakes.

To take into account all AM design possibilities and limitations, the first step is to reduce the part into its basic functional requirements (such as functional surfaces, load-case, etc.). This step allows the designer to only focus on the requirements and prevents him from limiting his design, hence maximizing the possible improvements. This can be especially interesting when dealing with assemblies (or even entire products).

To take full advantage of AM design possibilities, it is important to redesign conventional parts. AM-orientated design can be done in several directions:

- reduce the total number of parts
- design for functionality
- design parts to be multifunctional
- lightweight
- topological optimisation
- design for ease of fabrication
- design for material degradation and/or acceptable defects
- hybrid design solutions with combination of traditional subtractive manufacturing and additive manufacturing
- nature-inspired design.

From the functional requirements, the minimaum volume of material is then placed in order to link the surfaces and to sustain the load case (be it mechanical, thermal, coupled, etc.). This second step is usually achieved by using topology optimisation tools that suggest geometries able to sustain the loads while keeping the volume to a minimum.

The last step is to redesign the optimized volume in order to cope with the manufacturing constraints (such as angular orientation, machine dimensions, machining allowances, etc.). Since topology optimization leads to noisy geometries, caused by tessellation, it is usually necessary to implement model reconstruction and smoothing. This step can be very time-consuming, especially if the load cases that were used during the optimisation are very specific and do not take into account some steps of the product life cycle (such as machining which can require high rigidity).

Due to the nature of additive manufacturing process, the presence of structural imperfection defects is much harder to eliminate. They can exist in each layer or just in one of hundreds or thousands of layers, and can be extremely difficult to be inspect in a complex three-dimensional shape before evolving into mature defects. It is required to set defect acceptance criteria in the design stage as well as performance redundancy accounting for material degradation. However, there is lack of knowledge and experience of defects and material degradation obtained from AM technologies.

3.4 Part design and 3D CAD file generation software

AM Software can help to bring design enhancement, data preparation, automatic support generation, production management, workflow automation, machine communication and machine control.

Most of the general CAD softwares used to create components 3D representations are not specifically tailored for the design of parts made using AM. AM-specific design, rendered more complicated by the fact it is still a trial-and-error, experience-based activity is nevertheless critical to ensuring reliable and repeatable build success, improving production yield and minimizing post processing time and material waste.

AM machine requires CAD model of the part in the stereo lithography(*.stl) file format. The 3D model is converted into *.stl file format or digitalized into a mesh structure. At this stage, some meshing conversion errors can occur in *.stl file that may include gaps (cracks, holes, punctures, etc.), e.g. missing facets, degenerate facets (where all its edges are collinear), overlapping facets, non-manifold topology conditions. A repair software is necessary to check the tessellated model is valid. Such errors may be repaired automatically or manually using data preparation and build platform file manipulation software. It is also important to ensure fine meshing for precision and keep shape accuracy. The finer the mesh, the larger the *.stl file and this can eat up time during the slicing step but it's a small price to pay for realistic digitalization. ‘stl’ format contains only information on surface mesh and has no provision for representing colour, texture, material, substructure. AMF format version 1.1 is the new standard issued under collaboration between ASTM and ISO which address all the stl format disadvantages.

The first step in supports generation involves finding the most suitable part orientation to maximize build success and minimize the quantity of supports (hence limit wasted material and time consuming supports removal). It also means choosing the right type of supports with adequate part/support boundaries. This ensure 1) appropriate support and heat transfer and 2) this makes sure the first part layer in contact with the support structure is not peeling off due to insufficient heat transfer for example in SLS.

Slicing is the act of dividing the component and its support along its height in a finite set of layers along the z-axis (build axis) with user defined thickness. Specialized slicing software then slices 3D model into number of cross sectional layers. AM machine builds these layers one by one to manufacture complete part. Thickness of these layers depends on the type of raw material and the AM process used to manufacture the given part. Every AM manufactured part has inherent stair case like surface finish due to layer by layer build up approach. The supports need to be easy to remove and require only to be strong enough to support the build and withstand the re-coating motion with its potential “grating” effect. The supports are usually sliced with twice the thickness of the components and lower laser density processing parameters are used.

Once the components and supports *.stl files have been sliced, they can be loaded on the AM machine and respectively assigned suitable processing and “machine” parameters, previously determined during the critical process and parameters development stage. Building supports and components usually requires different respective parameters set, as the components require stringent mechanical properties, whereas the supports need optimized only for strength and easy removal. The substrate temperature, as well as machine and parameters for supports and components, are optimized during process development.

3.5 Feedstock characteristics

The characteristics of the feedstock wire or powder are critical to the quality of the AM process. Hence the quality and conformity of the incoming materials is critically important to the outcome of the part. Fundamentally, the challenge of improving part accuracy, surface finish, and performance start with the feedstock.

3.5.1 Powder as feedstock

3.5.1.1 Introduction

Metal powder plays a very important role in the additive manufacturing processes. The characteristics of powders used in additive manufacturing can have significant effects on process efficiencies and the quality of the final products. Powder sizes and morphologies need to be optimised for a particular process, and this requires a quality check on powder batches that are manufactured /purchased. The quality of metal powder used will have a major influence on mechanical properties but it can also influence:

- the build-to-build consistency
- the reproducibility between AM machines
- the production of defect-free components
- the manufacturing defects on surfaces and in the body.

3.5.1.2 Powder manufacturing processes

There are various technologies for mass metal powder production. One of the main requirements for using of metal powder in additive manufacturing and receiving reliable and repeatable results is a spherical form of particles. Some technologies allow to produce a spherical or near to spherical powder shape directly after synthesis of powder, whereas other technologies require a further processing to achieve the desired particles shape. Technologies for the production of metal powder conventionally are separated on base of the following methods: physical–chemical and mechanical ones. The physical–chemical methods are associated with physical and chemical transformations, chemical composition, and structure of the final product (metal powder) and significantly differ from raw materials. The mechanical methods include various types of milling processes and jet dispersion melts by high pressure of gas or liquid (also known as atomization).

Metal powders for additive manufacturing are usually produced using the gas atomization process, where a molten metal stream is atomized thanks to a high pressure neutral gas jet into small metal droplets thus forming metal powder particles after rapid solidification.

Gas atomization is a physical method (as opposed to chemical or mechanical methods) to obtain metal powders, like water atomization. Powders produced by gas atomization have a spherical shape, which is very beneficial for powder flowability while powders produced by water atomization will have an irregular shape.

Gas atomization is the most common process for additive manufacturing because it ensures:

- a spherical powder shape
- a good powder density, thanks to the spherical shape and particle size distribution
- a good reproducibility of particle size distribution.

Besides a very wide range of alloys can be produced using the gas atomization process.

3.5.1.3 Key powder characteristics

To reliably produce AM parts of acceptable quality it is important to understand the effect of powder characteristics on the part properties for powder-bed based AM processes. The three main areas that are important for characterizing a powder are particle chemical & metallurgical, morphological & geometrical, mechanical & physical (see Figure 6).

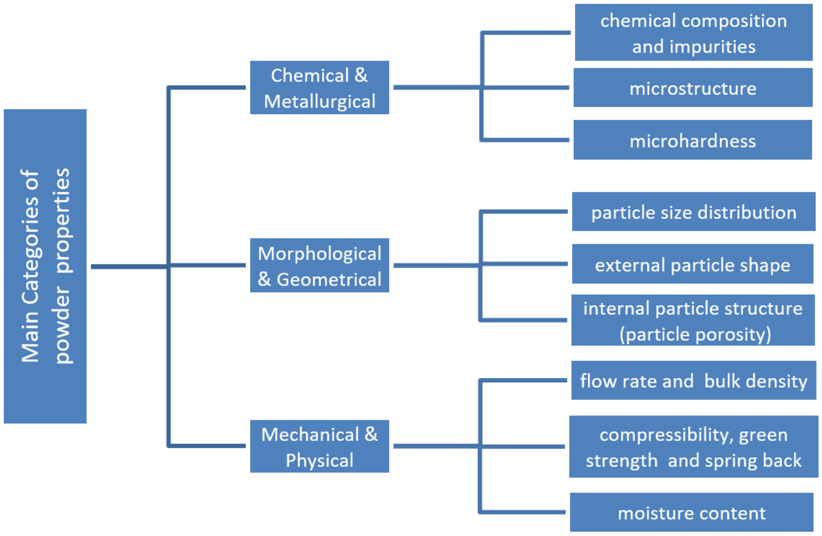


Figure 6 Classification of powder properties

Important metal powder characteristics for additive manufacturing are summarized below:

- chemical composition
- powder size distribution (PSD)
- moisture content
- pore size and shape
- surface area
- microstructure
- thermal properties
- density
- sieve analysis
- flowability
- apparent density
- skeletal density
- morphology.

In all cases, there are several useful existing standards to determine methods for characterizing metal powders, which have already been similarly applied to power metallurgy.

In AM, a powder that is deemed suitable in terms of size and chemistry is chosen whereby the process parameters are then optimized to yield parts of acceptable quality. However, it must be realized that tuning of powder properties must also be regarded as necessary. This can only be accomplished through the use of powder characterization methods to correlate powder characteristics to material properties. Table 3 gives a listing of commonly used powder characterization methods in AM, and organizes each into three categories: particle morphology, particle chemistry, and particle microstructure. When selecting and/or optimizing a powder for any given process, it is imperative that each is considered.

Table 3 Common powder characterization techniques used in additive manufacturing

Particle morphology	*Particle chemistry*	*Particle microstructure*
— Sieve analysis — Microscopy — Laser diffraction — Digital imaging.	— X-ray photoelectron spectroscopy — Auger electron spectroscopy — Energy dispersive x-Ray spectroscopy — Inductively coupled plasma optical emission spectroscopy — Inert gas fusion.	— Metallography — X-ray diffraction — Thermal analysis methods.

Additional points are important to consider when selecting metal powders for additive manufacturing processes.

- oxygen and/or nitrogen content
- storage and aging of powders
- reusability of powder after additive manufacturing cycles
- health, safety and environmental issues.

3.5.2 Wire as feedstock

3.5.2.1 Introduction

Wire feed systems work with traditional welding wire hence history and availability of welding wire provides a solid foundation for the qualification of wire feed materials feedstock. The primary characteristics of the wire are diameter and composition.

3.5.2.2 Key wire characteristics

The importance of consistency in wire diameter can be inferred from experiments such as the investigation of the effects of wire diameter and process rates on the deposition width and effects of relative position of wire tip to substrate and wire diameter/beam diameter ratio on build height consistency. All other parameters being equal, a larger diameter wire results in a larger deposition width but care must be taken to ensure that the laser or electron beam spot size is compatible with the selected diameter. Based on this guidance, is seems reasonable to conclude that variations in the wire diameter throughout the length could impact the geometric accuracy of the build. Similarly, matching the distance between the wire tip (where the droplet detaches) and the substrate to the process characteristics is critical to achieving preferred deposition characteristics: that the droplet touches the substrate before detaching to create a smooth deposition layer. Variation in wire diameter that raises the tip above the smooth detachment point could therefore lead to geometric distortion in the part's height.

Standards such as AWS A5.4 set tolerances on diameter in the range of ±0.05 mm. Deviations in deposit width could potentially be accommodated through detection of diameter change and subsequent alteration of feed and translation rates.

3.6 Material anisotropy and resulting properties

The material properties obtained with additive manufacturing processes are unique and specific for these technologies, due to the small melting pool and rapid solidification.

Mechanical properties of parts produced by additive manufacturing are usually:

- superior to the properties obtained with investment casting process
- inferior or sometimes close to the conventional wrought part.

Key features of materials produced by additive manufacturing are:

- the fine microstructure, due to the very rapid solidification process
- a slight anisotropy in Z direction (building direction), which induces slightly lower mechanical properties due to the superposition of layers. Anisotropy can be avoided in X and Y directions by using an adapted laser scan strategy.
- a few small residual porosities, in particular below the surface. However, densities of 99.9% are commonly reached with additive manufacturing processes. To achieve full density, post processing by hot isostatic pressing (HIP) can be done, like for parts made by investment casting.
- likely less corrosion resistance and fatigue-fracture resistance.

One aspect of AM that needs to be addressed is material anisotropy. Variations in material properties are inherent with AM techniques, as they produce parts layer-by-layer. However, designers can also apply varying parameters on purpose, to create gradient materials properties that may be desired for the part.

When a part is manufactured by powder bed fusion or DED, the material properties may be more isotropic than with other AM methods such as material extrusion which relies on directional material flow or sheet lamination which is subject to the anisotropy of the sheets used as feedstock for the process. If the method of manufacture does not generate isotropic material, then it will need to be accounted for in the design. This can be done either by calculations that are with and against the “grain” of the final material, or by a finite element analysis (FEA) capable of realistically modelling anisotropic material.

Material inhomogeneity was found in recent experiments to result in greatly accelerated failure of AM specimens tested in high and low concentrations of H_2S. These parts were tested against welded and wrought specimens, and failed in a short period of time. The researchers found discontinuities in the polished surface, and concluded that this played a role in the failures. However, it was also determined that additional testing is required. Using a TQ process as put forward in this paper, one could perform testing to see if AM produced parts are appropriate for use in sour service.

3.6.1 Role of part orientation and support structure in product quality

The orientation of parts in the powder bed is a key point of attention both for quality and cost. Indeed, part orientation influences the build time, the quantity of supports, the surface roughness and residual stresses.

Finding the best suitable part orientation helps achieving:

- the shortest build time i.e. minimizing the number of layers and part height
- the minimal amount of supports and less overhanging features
- an easy access to supports so that they can be easily removed
- the best possible surface roughness and minimal staircase effect
- the minimum level of residual stresses which can lead to part distortion
- supporting structure for any overhanging parts having less than 45deg angle from the horizontal axis may be omitted.

3.6.2 Role of process parameters in improving material properties

To achieve high mechanical strength and adequate fatigue behaviour, it is important to produce high density parts with optimal surface quality and to minimize defects, through the optimization of process parameters. In this way, a working window is obtained with a define set of laser parameters where parts with high densities and low roughness are guaranteed.

In laser processes, the energy density (E) is a key factor:

- sufficient energy density is needed to melt powder particles of the layer being processed and of the previous layer to assure a correct joining between successive layers and avoid lacks of fusion and porosity
- excessive energy can cause vaporization of the material creating defects and reducing material density, and result in heat affected zone (HAZ) altering material microstructure.

The optimization of parameters shall be done both for the interior of the part and for the borders, where a good balance of minimized defects in the sub-surface and low roughness is pursued. To optimize parameters, it is a common practice to manufacture simple geometries like cubes maintaining constant the power and varying the scanning speed in each cube, for a given layer thickness and hatch spacing. Thus, each cube is manufactured with different energy density. Afterwards, the cubes are characterized where interior density, sub-surface density and roughness are determined, so as to identify the right energy density window and corresponding parameters. For the parts of complex geometries, the optimization of process parameters is usually much more sophisticated and may be independently tuned for specific printed part.

SECTION 3 QUALIFICATION AND CERTIFICATION PROCESS

1 Introduction

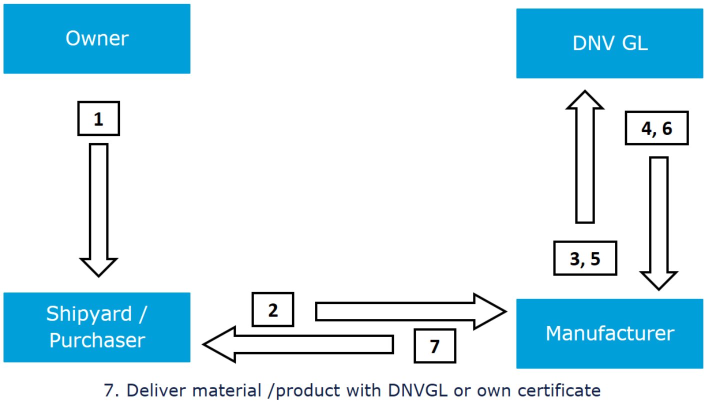
This section contains methods, technical requirements, principles and work procedures related to qualification of AM processes and certification of AM products.

2 Certification scheme for materials and components

2.1 Current certification regime for materials and components

DNV GL certification of materials and components (CMC) services ensure that materials used, and components and systems installed on vessels classed by the Society comply with the rule requirements. The value of the CMC services for the Society’s customers is that compliance with the requirements is verified and documented, and that this is done in an efficient and cost-effective way by competent personnel.

DNV GL rules and supporting documents have an established certification regime for materials and components manufactured through conventional manufacturing technologies as described in a simplified flow chart in Figure 1 and described in detail in further sub-sections.



1. Order a vessel with DNVGL class
2. Order material/product with DNVGL certificate
3. Request for DNVGL AoM or TA
4. Deliver DNVGL AoM / TA
5. Request for Certification of material
6. Certify material/product
7. Deliver material /product with DNVGL or own certificate

Figure 1 Class certification regime for materials and products/components

2.1.1 Materials certification

2.1.1.1 Approval of the manufacturer

The DNV GL approval of manufacturer (AoM) scheme is a procedure by which the Society approves manufacturers for supply of products in accordance with the Society's rules and standards.

For a description of general requirements, conditions and procedures related to the approval of manufacturer scheme, see DNVGL-CP-0346.

2.1.1.2 Testing and inspection of the individual materials

For a description of general requirements, conditions and procedures related to the certification of materials and components, please refer to class program DNVGL-CP-0337.

2.1.2 Product certification

Product certification based on the rules, will in most cases include the following two main elements:

— approval of the product design, and
— survey during the production and/or of the final product.

The applicable chapters of the Society's rules define the extent of the certification required. The survey will be carried out at the manufacturer’s premises. The design approval will either be on a “case by case” basis, or follow the procedure for type approval.

For a description of general requirements, conditions and procedures related to the type approval scheme, see DNVGL-CP-0338.

3 Qualification and certification framework for additive manufacturing products

3.1 Introduction

The rapid emergence of AM technologies and manufacturers that offer these services creates new opportunities for end users but this process also generates a continuous amount of change that could compromise quality and safety. For example, machine suppliers are testing limits to develop higher powered lasers to speed up the manufacturing process. They are also looking at how to recycle or reuse more powder from each manufacturing cycle to save on costs. While the scale of energy and final products encourages the use of large format printers, a closer examination of these printed parts suggests a lack of readiness of these systems for fabricating structural components. A reliable certification system could act as a stabilising force for quality and safety hence establishing such system is the need of the hour.

3.2 Comparison between qualification and certification processes

Table 1 Typical characteristics of qualification and certification processes

Criteria	*Qualification*	*Certification*
Scope	Process of evaluating a prototype design/material / product during the development/testing phase to determine whether that meet the specified requirements for that phase.	The process of evaluating a material /product / component during or at the end of the development process / regular production to determine whether it satisfies specified technical requirements.
Objective	To ensure that the design/product is being designed/built per the set requirements. In other words, to ensure that prototype meet the specified requirements to go to validation phase.	To ensure that the product meets the rule requirements, user’s needs, and that the specifications were correct in the first place. In other words, to demonstrate that the product fulfills its intended use when placed in its intended environment.
Question to address	Are we designing/ building the product, as per requirement?	Are we building the *right* product?
Evaluation Items	Feasibility reports, requirement specs, design specs, software code, test cases, procedure qualification, process parameters, etc.	The actual product/software.

Criteria	*Qualification*	*Certification*
Activities	— reviews — audits / site-visits — witness testing — compliance statement — facility approvals	— inspections — testing — product certification

3.3 DNV GL's certification pathway for additive manufacturing products

AM is an emerging technology which has not yet been widely adopted as an alternative manufacturing processing route to produce certified components for ships or offshore structures according to DNV GL rules and offshore standards. Hence DNV GL will not apply traditional qualification and certification approach to AM manufacturers and products. Approval of AM processes and parts will be dealt with on a case-by-case basis as illustrated in Figure 2 Certification pathway for AM products for class.

The certification pathway described in Figure 2 can be related to three phases of deployment of a new technology as illustrated in Table 2. I.e. procedure qualification, approvals, certification of materials/ components.

Phase -1: Procedure qualification phase, where manufacturers or end users run qualifications/ the proof of concept to prove that they have feasible technology /products. In this phase, technology assessment and manufacturing procedure qualification activities mentioned in the Table 2 are relevant.

Phase -2: Approval phase, where manufacturer's or end user's design or manufacturing capabilities and process controls are assessed to determine if the manufacturer can produce specific grades or types of materials that conform to the Rules. In this phase, relevant approval(s) among 'approval of manufacturer, type approval / case by case design approval or approval of service supplier' as mentioned in Table 2 shall be applied and obtained.

Phase -3: Certification phase, where manufacturers /end users require DNV GL to certify material or products from regular production, either as individual parts or in batches, depending on the certification requirement of those parts. Material certification and component /product certification mentioned in Table 2 are relevant activities in this phase. DNV GL's involvement in this phase is mainly related to repetitive inspection and certification activities.

Since this class guideline is mainly written for the maritime classification applications, certification pathway for AM products for non-class or voluntary applications as illustrated in Figure 2 is limited up to procedure qualification phase. Feasibility study and technology qualification are the main activities for non-class/ voluntary applications. Since class approvals as described in phase-2 above, paragraphs are not relevant for non-class applications. Certification or verification activities for such applications may be considered after successfully completing the technology qualification.

Table 2 Requirements during qualification, approval and certification regimes

Regime	Activities
Qualification	Technology assessment Manufacturing procedure qualification
Approval	Approval of manufacturer Type approval Approval of service supplier
Certification	Material certification Product certification

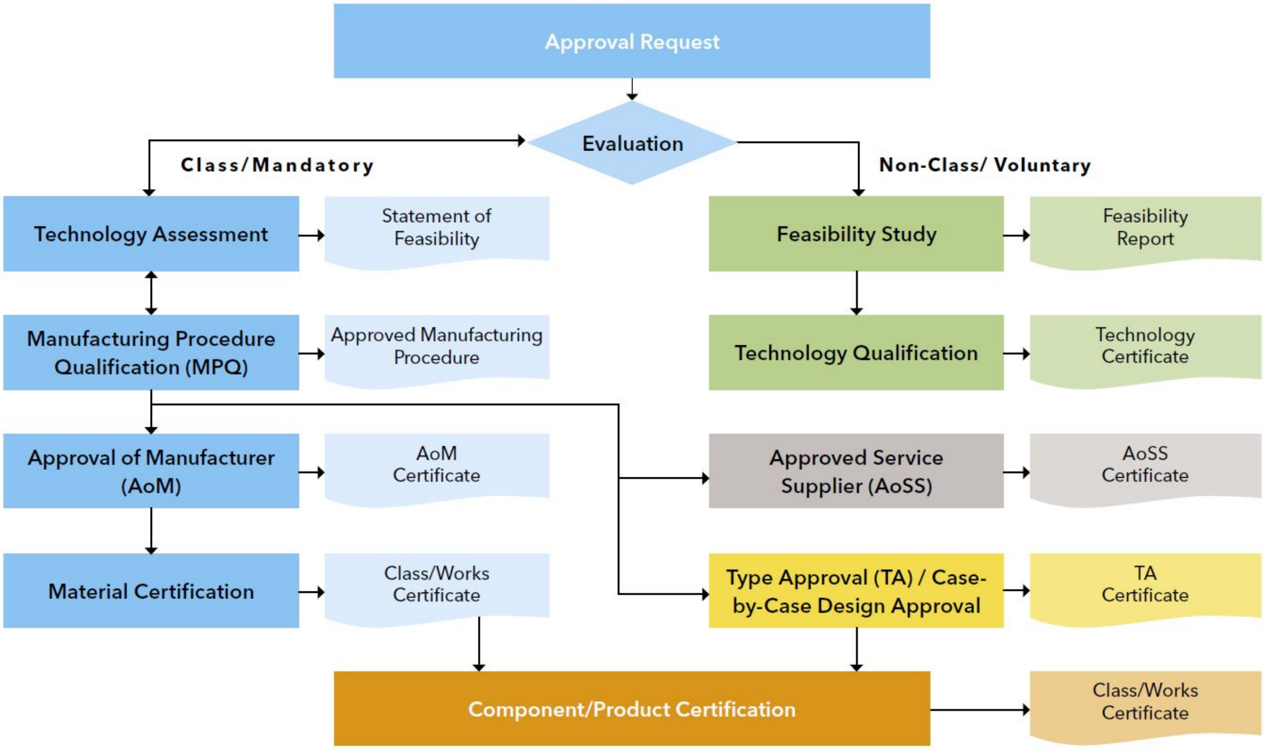


Figure 2 Flowchart illustrating certification pathway for additive manufacturing products

3.4 Qualification regime

3.4.1 Introduction

This section presents a general overview of the manufacturing procedure qualification process (MQP). The activities and documents involved are briefly described. The qualification process ensures that the specified method, by which the parts are processed, is able to meet the qualifying criteria in a repeated manner in order to be identified as qualified. The aim of the qualification process is to identify the variables of the process and its allowance range in order to know their influence in the part performance and process reproducibility. Thereby, qualification process provides a correlation between product and process specifications to ensure adequate and consistent performance of parts, the procurement procedures, and assessment procedures for part acceptance. Reverse engineering approach, i.e. printing a new product by scanning an existing product, may require to consider intellectual property (IP) issues which shall be addressed on a case-by-case basis.

The qualification process shall comply with three important aspects related to the quality assurance:

- Technical requirements: the resultant part among the process specified meets the technical requirements for such component.
- Repeatability: it is possible to reproduce the same result all the time and through different batches or orders.
- Traceability: it is possible to know the complete history of each component from the concept, through the raw material to the final product.

Table 3 describes the qualification process for AM products that defines a two-stage qualification approach.

Stage 1: Material integrity testing through manufacturer and process qualification

During this stage the focus is on material integrity testing, where first a manufacturer is required to obtain a 'statement of feasibility' through:

1) technology assessment process
2) establish and qualify manufacturing procedure qualification
3) apply for approved manufacturer status under approval of manufacturer scheme.

Stage 2: Functional testing for intended use or fitness for purpose

During this stage AM process technologies used, or components produced by an AM process are considered fully qualified for their intended use when:

1) the failure modes that have been identified through the systematic process have been properly addressed
2) the supporting evidence substantiates that the technology or component fulfills all stated functional requirements and meets the stated reliability target.

Table 3 Stages in qualification process

	Stage 1: Material and process qualification	*Stage 2: Component qualification*
Technology assessment	Material and process assessment	Design and functional requirements assessment
Manufacturing procedure qualification	Material qualification testing	Functional qualification testing

Sequence of various activities during manufacturing procedure qualification is described in Sec.3 [3.5] and summarised in tabular form in App.A.

3.5 Sequence of various activities during manufacturing procedure qualification

3.5.1 Kick-off meeting

A kick-off meeting shall be held at appropriate time and is intended to:

- clarify the qualification scope and requirements
- present the scope of work as agreed in the contract
- obtain information related to the manufacturing facilities and testing laboratories
- agree upon the documents to be submitted
- agree upon the project schedule
- present DNV GL's expectations to the manufacturer
- review the documentation related to the manufacturer's experience and/or any trial productions.

3.5.2 Scope of work

The scope of work shall be determined in cooperation with the customer. The following shall as a minimum be agreed on:

- Extent of qualification: the number of manufacturing sites and processes, material grades, product forms, wall thicknesses, weight, etc.
- Extent of the document review: the mandatory documents and procedures, number of review cycles and inspection test plan (ITP).
- Extent of witnessing activities and hold points: the number and duration of site visits. This will depend on the manufacturer's previous experience with AM process.

3.5.3 Qualification parameters

The manufacturer shall define the project's parameters, such as the production site, production route, type of product, material grade and size range.

The choice of parameters should be guided by the following:

- If the manufacturer is aiming for a specific project, it is recommended to use the parameters defined by the potential customer.
- If the manufacturer is aiming for general commercial purposes, the parameters should reflect the manufacturer's capabilities and the intended market for the product to be qualified.

Additional requirements may be applicable through project specification but the qualification process shall fully comply with DNV GL rule requirements. The project specification can be referenced in the DNV GL qualification report if any supplementary requirements to the previously mentioned standards shall be considered.

3.5.4 Initial review and verification

The qualification documents shall be prepared prior to the start of the qualification process. The manufacturer's summary and related procedures shall describe the steps in the manufacturing facility/ route that is being qualified and shall present the activities carried out to meet the set requirements

3.5.5 Site visit – witnessing of the qualification

The qualification plan forms the basis for the witnessing activities.

All activities noted in the qualification plan shall be witnessed for at least one representative process/ material/component to be qualified and subsequently reported in a site visit report. The capability of all equipment used in the qualification process shall be verified as part of the witnessing activities. All equipment shall be fit for purpose: properly identified, regularly maintained and calibrated as per set requirements; all calibration certificates shall be available upon request.

The final stage of the qualification is the material testing of the component. Sampling of test coupons and material testing shall be witnessed by DNV GL. The laboratory facilities shall be assessed by the TA before testing in accordance with agreed requirements. The DNV GL site visit team shall not face any restrictions on access to the production facilities during the qualification process.

3.5.6 Final report by manufacturer

On completion of the qualification testing, the manufacturer shall prepare and submit a detailed report. The report shall include the information on manufacturing route and equipment, documentation of all relevant tests and test results, and include original test records endorsed by the surveyor. The language of the submitted documentation shall be English. Incomplete report, or test results not complying with the given requirements may be returned to the manufacturer for correction.

3.5.7 Evaluation by DNV GL

The evaluation of compliance with the requirements is based on the final report, the site visit surveys, and the survey report. In case of insufficient documentation or test results, the manufacturer will be informed for further actions.

3.5.8 Statement of qualification

3.5.8.1 Issuance of a Statement of Qualification

Appropriate deliverable as described by this class guideline shall be issued by DNV GL as a statement confirming that the document verification and qualification activities have concluded that the object complies with the relevant requirements. Any limitations will also be described.

3.5.8.2 Validity of the statement of qualification

Any essential change in the procedures and process/ equipment shall require re-qualification.

3.6 Approval regime

Despite recent advances in the additive manufacturing sector, quality issues could remain a frequent occurrence, and can result in fatal accidents, equipment downtime, and loss of life. Adequate quality is of high importance in high-risk industries such as seagoing vessels and offshore installations in which third party quality assurance and product control play an essential role in ensuring manufacturing quality of critical components.

DNV GL make sure that all the stakeholders i.e. manufacturers, builders, and end users are provided with adequate rules and standards that effectively ensures components are produced at a high level of quality based on the area of application . Quality issues have also been linked to the lack of competence or negligence of stakeholders in the supply value chain. However, continued actions and regulatory reforms through modernization of rules and requirements has provided additional tools for purchasers and manufacturers to confront these issues.

As part of this process, DNV GL will evaluate AM manufacturers' ability to consistently manufacture and deliver products to the requirements set by the rules by using various methods such as design assessment, plant audits, manufacturing survey, inspection and certification activities, etc.

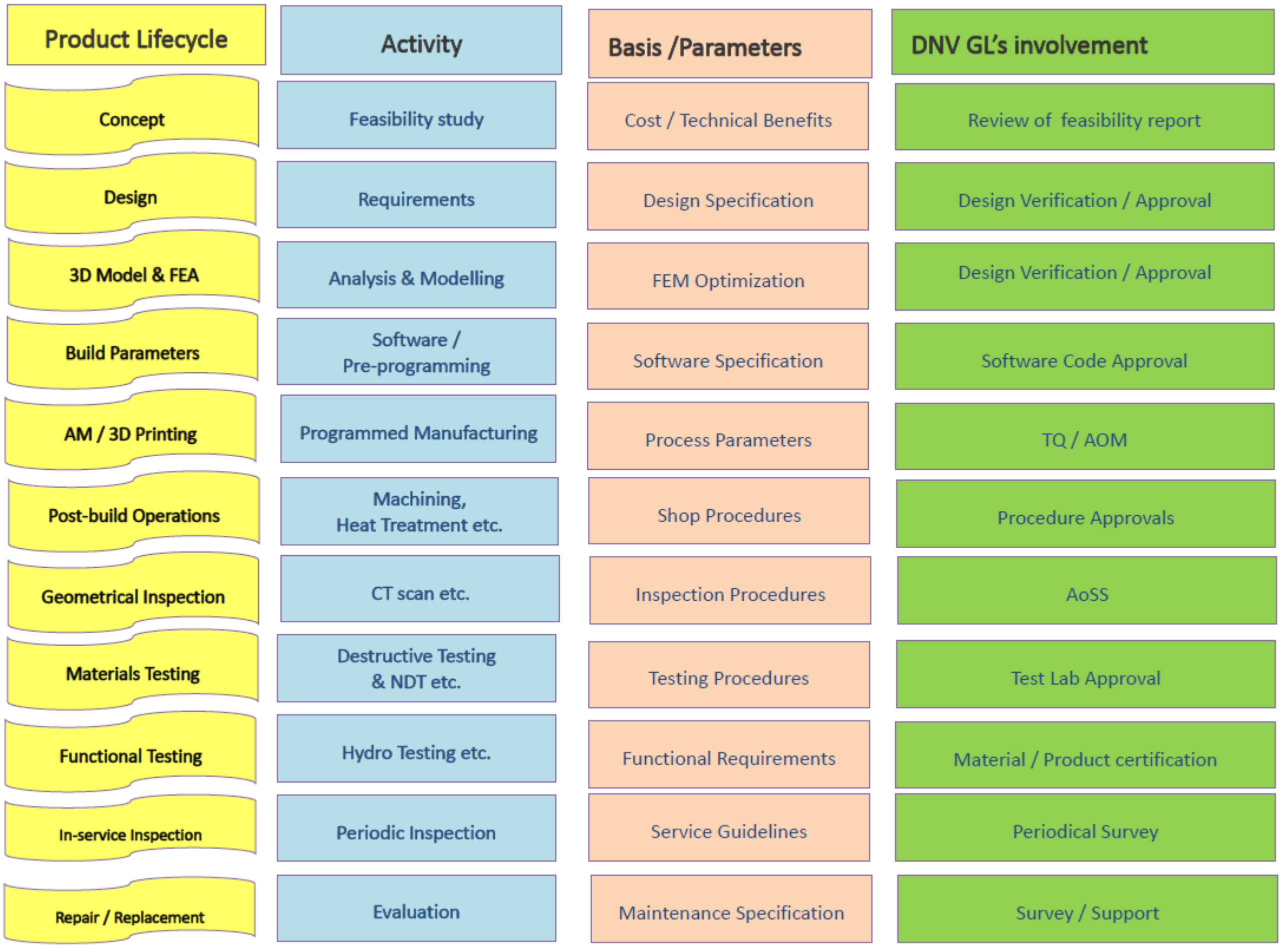
An overview of DNV GL existing classification services that are relevant for AM materials are summarized in Table 4, Table 5 and Table 6.

Table 4 Typical areas for seeking DNV GL approval

Involvement in AM product life cycle	*Process related*	*Materials/ component related*	*Organisation related*
Design	— Design assessment	— Case by case approval — Design approval	— Approval as sub-supplier
Feed-stock	— Manufacturing process approval — Accreditation of equipment — Approval of consumables	— Raw materials inspection / certification — Approval of material safety data sheets — Case by case approval	— Approval as manufacturers — Approval as sub-supplier
Pre-processing	— Verification of design file and cyber security — Verification of build layout with orientation, support structures & test specimens — Integrity of software/firmware	— Review of 3D model for manufacturing	— Cyber security compliance review
3D Printing / manufacturing	— Approval of process parameters — Accreditation of AM equipment — Approval of operating procedures	— Approval of manufacturing procedure qualification	— Certification for operators — Approval as manufacturers — Approval as sub-supplier
Post-processing	— Approval of operating procedures.	— Procedure for extraction of test specimens	— Certification for operators — Approval as manufacturers — Approval as sub-supplier

Involvement in AM product life cycle	*Process related*	*Materials/ component related*	*Organisation related*
Testing and inspection	— Approval of testing and inspection procedures — Accreditation of testing equipment	— Witness / survey reports	— Approval as sub-supplier
Certification	— Regular, periodical and unscheduled audits	— Inspection reports — Issuance of certificates	— Approval as manufacturers — Approval as service-supplier

Table 5 Various activities in the additive manufacturing product life cycle and the relevant DNV GL approval services.



Product Lifecycle	Activity	Basis /Parameters	DNV GL's involvement
Concept	Feasibility study	Cost / Technical Benefits	Review of feasibility report
Design	Requirements	Design Specification	Design Verification / Approval
3D Model & FEA	Analysis & Modelling	FEM Optimization	Design Verification / Approval
Build Parameters	Software / Pre-programming	Software Specification	Software Code Approval
AM / 3D Printing	Programmed Manufacturing	Process Parameters	TQ / AOM
Post-build Operations	Machining, Heat Treatment etc.	Shop Procedures	Procedure Approvals
Geometrical Inspection	CT scan etc.	Inspection Procedures	AoSS
Materials Testing	Destructive Testing & NDT etc.	Testing Procedures	Test Lab Approval
Functional Testing	Hydro Testing etc.	Functional Requirements	Material / Product certification
In-service Inspection	Periodic Inspection	Service Guidelines	Periodical Survey
Repair / Replacement	Evaluation	Maintenance Specification	Survey / Support

Table 6 Applicable DNV GL service based on position in value chain for additive manufacturing products and service

Position in the value chain	Typical activity	Feasibility Study	Technology Qualification	Technology Assessment	Manufacturing Procedure Qualification	Approval of Manufacturer	Type Approval	Material/ Product certification
Designer	Design of products for end-use or functionality	●	●	●			●	
Manufacturer	Raw material producer (powder/wire etc.)	●		●	●	●		●
	Print 3D products using own printing facility	●		●	●	●		●
	Manufacturing support such as HT etc.	●		●	●	●		●
	Product manufacturer	●		●	●	●	●	●
Sub-supplier	Producer of 3D printing machine or other essential accessories	●	●	●	●			
	3D modelling of product / support structures etc.	●		●				
	Simulation of process parameters	●	●	●				
	Process optimization software	●	●	●				
	Preprocessing or post processing optimization	●		●				
	Online or offline process monitoring	●		●				
	R & D establishment	●		●				
	Testing of 3D printed parts (mechanical testing or Non-destructive testing)	●		●				
	Training provider - Universities / Training institute	●		●				
Fabricator	Ship yard, port, repair yard etc.	●	●	●	●			
End-user	Ship owner, Machine builder etc.	●	●	●				

APPENDIX A SEQUENCE OF ACTIVITIES DURING AN EXAMPLE MPQ PROCESS

Table 1 Typical procedure to be followed for manufacturing procedure qualification

Step No.	Activity	Action	Responsible
1	Request	Identify process/product for qualification	**Customer**
2	Follow-up	Qualification requirements, quotation, kick-off meeting, project set-up, agreement signing	**DNV GL & Customer**
3	Initial documentation	Establish procedures/specifications: a) component requirements specification b) pre-manufacturing procedure summary (pMPS) c) plan for data acquisition and process monitoring d) parametric window for process with limits for essential variables e) preliminary testing and inspection plan (ITP) f) facility description and other details	**Customer**
4	Initial review	Review and approve or request more information if necessary, in such case review and approve revised documentation.	**DNV GL**
5	Audit request and further documentation	Prepare for facilities audit and invite the AM expert, establish procedures for: a) raw materials quality & inspection b) 3D model generation including any supports c) verification of 3D model and its security/ integrity d) 3D printing process and post processing e) identification, traceability and its verification f) procedure qualification test plan (PQT) with type and number of tests g) 3D printing machine's repeatability	**Customer**
6	Site visit & witness	Works survey, give comments as applicable	**DNV GL**
7	Manufacture	Execute PQT/produce test products under AM experts witnessing and verification of process data acquisition, stamping of test products	**Customer**
8	Qualification testing	Carry out required under DNV GL witnessing	**Customer**
9	Report preparation	Prepare a report i) summarise test results ii) document the data acquired and analyses, correlate with physical products properties iii) make a comprehensive report correlating process-structure-properties	**Customer**
10	Review reports	Approve or request more information or require new production/ testing if necessary	**DNV GL**
11	Finalize documents	If approved modify pMPS into MPS based on approved PQT parameters, propose a plan for reduced testing and inspection for actual production and resubmit	**Customer**
12	Reduced testing	Carry out qualification procedure for reduced testing during regular production and get it approved	**Customer**
11	Completion	Issue and forward the statement of qualification	**DNV GL**

APPENDIX B TESTING OF ADDITIVE MANUFACTURING COMPONENTS

1 General overview of testing methodology for additive manufacturing parts

1.1 Introduction

Materials and processes used to produce components for maritime applications shall first be formally qualified. While qualification procedures vary depending on application, the goal of qualification can be summarized as the collection of sufficient data to demonstrate that a material or process will function as expected. Extensive empirical testing to fully qualify a material often requires many thousands of individual tests and may take several years to complete. Further, a minor change in the process requires complete re-qualification. The variety of AM processes available to users and the variety of process variables used to produce an individual part make statistical-based qualification through empirical testing particularly burdensome. Currently no AM processes or materials are qualified for maritime applications. Non-critical AM materials and processes can be qualified using empirical testing with fewer tests, but the cost and time remain high, encouraging companies to keep the resulting data proprietary.

There are generally three different paths to qualification:

1) statistical-based qualification rooted in extensive empirical testing,
2) equivalence-based qualification achieved through moderate testing to demonstrate a new material or process is equivalent to a previously qualified material or process, and
3) model-based qualification where a material’s or process’ performance is demonstrated in a computer model and verified with minimal testing.

Developing the test methods and protocols to support equivalence-based qualification and model-based qualification will enable AM users to qualify materials and processes without the high cost and time required by statistical-based qualification and without the high level of uncertainty associated with model-based qualification. DNV GL with its extensive experience and its standing as a neutral third party is in the process of developing test methods and protocols, provide reference data, and establish minimum requirements needed to achieve more rapid qualification. That will ease the qualification process in maritime applications, and lead to a better understanding of AM and more confidence in AM products used in. However, that process will take some years.

1.2 Different strategies for qualification of additive manufacturing parts

There have been several breakthroughs of producing metallic components by additive manufacturing, however the bulk production and application of those parts as functional components are still very limited. In order to have AM components as the replacement of traditional components, they have to undergo the same testing procedures as defined in standards or industrial specifications as the traditional manufactured components. The inherent characteristics of AM processes require additional consideration of testing for qualification and certification to achieve the same level of safety assurance. The extent of testing depends on the criticality of the AM part and the operating environment in service.

This appendix provides an assessment of the challenges of testing AM components in comparison with the traditional manufacturing processes, with an emphasis on the production of AM metallic parts.

Due to the nature of AM process, parts are often highly anisotropic and caution has to be taken to ensure correct testing and buildup direction. Metal additive manufacturing parts are often made from metal powder and supplier of metal powders do not provide mechanical properties of the material but powder properties instead. Build parameter like scanning strategy, hatching distance and temperature can interact together and affect final part properties. Metal AM parts have their benchmarking of required strength to conventional material which are produced by rolling, casting and forging.

1.2.1 Statistics-based legacy qualification processes

The traditional product qualification requires extensive testing to establish the distribution of materials performance from a specific manufacturing process and further define the confidence level of material, which may take years to collect enough data. The subsequent subtractive machining for the final product largely preserves the same materials properties. While the production of AM components is a relatively independent process for each part even they are produced from a single build cycle. The lack of an adequate understanding of complex AM processes and in-situ process monitoring can result in mechanical properties of final product that vary depending on the machine used, part geometry and the dynamics of the build process. It has been found that variations exist across nearly all material properties for critical AM component. Material performance also vary with powder characteristics, build direction, layer thickness, processing parameters, and many more variables. On the other hand, testing on a large population of AM parts to obtain statistics data is also not economically feasible at current stage. A new statistic view of materials properties with respect to AM process shall be investigated with incorporation of in-situ process control and non-destructive examination.

1.2.2 Sampling strategy for additive manufacturing component testing

Well-known statistic data of traditionally manufactured products allows simple sampling strategy to choose limited number of products to be tested, and the results represent the overall large population of products. The inherent variability of material properties for AM components requires a different route for small volume group. The current strategy to select AM samples for destructive testing is: 1) test artifact prior to the AM production and 2) witness specimen after the AM production.

A test artifact, intended for standardization, quantitatively characterizing the consistent performance of AM systems. Most of the test artifact designs have various “real” features built in a variety of sizes, locations, and orientations, and potentially would be supplemented with selected real parts. Test artifacts are mostly used for optimizing the AM process parameters for better material properties. Imperfections can form at any time during manufacture, installation and service, which can evolve into defects that have a significant risk of causing a failure. In contrast to traditional wrought parts, there are some new defects unique to AM process and difficult to be inspected. A test artifact with intentionally built imperfection/defect will assist the justification of defect acceptance criteria for AM components.

A witness specimen is designed for a variety of tests while it is built along with AM components from the same build cycle. Except the dimensions and geometry, witness specimens experiences the same feedstock of metal powders, chamber environment, identical or similar process parameters and post-process treatment. The witness specimens are likely to have the same properties as the actual AM components built with a robust manufacturing plan. According to ASTM standards F2971, witness specimens for tension testing shall be machined from bulk deposition near net shape components and built in four orientations (X, Y, XY, and Z) in accordance with ISO/ASTM 52921. The location of witness specimens within the build volume also needs to be reported. As a result of different geometry and variation during manufacturing, there is lack of confidence in representing the properties of real AM components by those limited number of witness specimens.

1.2.3 Specified testing as per the functionality of additive manufacturing components

AM technology is known for its “complexity for free” attribute as a highly customizable manufacturing process for small volume production. Because of different design functionalities and service conditions, specific testing requirement shall be applied on a case by case basis, not based on materials only. For instance, the AM component produced from the same alloy feedstock powder, in which one will be used as spare parts for the purpose of design redundancy and the other one will be used as critical structural component in severe conditions, should not be treated equally. More testing and strict specification may be required later. Also the presence of unavoidable imperfections/defects in the AM component demands a methodology for assessing the fitness for purpose of AM parts.

On the other hand, the development of testing standards typically evolves behind the industry advance. There are a number of new testing technologies (primarily non-destructive) emerging for the AM technologies, which have not been recognized and standardized by regulators yet. Therefore, the testing of AM component will likely be customized with respect to the applications and the risk associated.

1.2.4 Reliability and accelerated laboratory testing

Besides rigorous and repeatable AM production quality, long-term performance and degradation of AM material also challenges the penetration of AM into several industries that have the minimum risk tolerance. As the results of AM processing characteristics, the degradation of AM materials may have unique behaviour and alter the rules established for traditional wrought counterparts which have been backed by sufficient history data. Due to the lack of long-term performance data, reliability of functional AM components can be investigated by accelerated laboratory tests. The experiment combined physics models or probabilistic cause-effect relationship approaches, enable quantitative assessment to bridge the gap between accelerated laboratory testing results and long-term performance, as well as assist in prioritizing/redefining accelerating vectors in the laboratory test. Considering all the unknowns and uncertainties on this route, periodic inspection shall be performed and documented for the employment of AM parts meeting specification for wrought counterpart as critical structural components. It also serves a reliability data base to validate developed model.

1.3 Testing methods for additive manufacturing component

1.3.1 Destructive testing methods

Although the inherent characteristics of AM process prefer NDT for product qualification regardless of geometry and materials, destructive testing is capable of capturing the response of fracture and cracking on AM components. A destructive testing is usually conducted on test artifacts, witness specimens or spare/dummy AM parts. Some research efforts have been carried out on developing correlation between NDT results and fracture behaviour. An overview of how existing testing standards may relate to mechanical properties of AM materials has been given in ASTM F3122. Some destructive testing methods for AM are summarized in Table 1. Detailed destructive testing can be done on the prototype and essential regular testing may be established for the intended usage of the AM components.

Table 1 Destructive testing methods used for additive manufacturing components

Brinell hardness test	hardness, 10~35 °C	ASTM E10, ISO 6506-1
Charpy and izod tests	fracture toughness	ASTM E23, ISO 148-1
Compact tension (CT) sample test	fracture toughness, plane-strain	ASTM E399, ISO 12737; ASTM 1820, ISO 12135
Compression test	cellular structure	ASTM E9, ISO 13314
Crack Growth test	(fatigue) crack growth rate	ASTM E647, ISO 12108
Cyclic-potentiodynamic polarization (CPP)	localized corrosion	ASTM G61, ASTM F2129
Fatigue bending test	fatigue	ASTM E466, EN 6072
Fatigue load increase or constant amplitude test	fatigue strength, S-N	ASTM F3122, ISO 14801
Fatigue test, strain controlled	fatigue, 10~35 °C	ASTM E606, ISO 1099
Fatigue test, thermomechanical	fatigue, strain controlled	ASTM 2368, ISO 12111
Potentiodynamic polarization (PDP)	corrosion behaviour	ASTM G5
Quasi-static tensile test	strength, modulus, 10~38 °C	ASTM E8/E8M, ISO 6892-1, EN 10002-1
Rockwell B, C hardness test	hardness	ASTM E18, ISO 6508

Static immersion test	uniform corrosion by weight loss or metal release	ASTM G31, ISO 10271
Tensile test at elevated temperature	strength, modulus, >38 °C	ASTM E21, ISO 6892-2
Tensile test at low temperature	strength, modulus, <-196 °C	ASTM E1450, ISO 19819

1.3.2 Non-destructive testing of additive manufacturing parts

Due to the inherent variability and uncertainty of AM process, non-destructive testing (NDT) can be a promising solution for qualification and certification of AM parts and impacts all aspects of AM. Various NDT methods have been employed not only on the finished AM metallic components, but also on in-situ monitoring for process control. The primary application of NDT as a materials characterization tool will be to detect larger scale defects (non-rejectable) and flaws (rejectable) in as-manufactured and post-processed AM parts, and monitor the AM process. NASA recently published a state-of-the-discipline report on non-destructive evaluation of AM system. As ASTM E07 NDT committees are working in collaboration with F42 AM committees on NDT of additively manufactured part standardization. Some of NDT methods for AM are summarized in Table 2.

Table 2 NDT methods used for additive manufacturing components

Eddy current testing (ET)	surface critical defects	ASTM E2884
Electrochemical impedance spectroscopy (EIS)	electrochemical impedance, corrosion behaviour	
Helium psychometry (HP)	density of particles	ASTM B923
Impulse excitation of vibration	elastic modulus	ASTM C1259
Inert gas fusion method	oxygen/nitrogen content	
Laser diffraction particle analyzer	size distribution of metal powder	ASTM B822, ISO 13320, MPIF Standard 1
Near infrared (NIR) thermal imaging	in situ process monitoring of melt pool	
Neutron diffraction (ND)	internal stress, residual stress	
Phased array ultrasonic testing (PAUT)	embedded voids or weak deposition layers	
Polarization resistance (Rp)	corrosion rate	ASTM G59
Profilometry	surface roughness, morphology	
Scanning auger electron microscopy (SAM)	elements variation due to corrosion	
Scanning electron microscopy (SEM) and energy dispersive x-ray (EDS) analysis	particle morphology, shape, size; elemental composition near surface, microstructure, phases	
Laser ultrasonic testing (LUT)	in-situ AM process monitoring	
Ultrasonic testing (UT)	surfaces embedded voids or weak deposition layers	
X-ray computed microtomography (μ-CT)	high resolution of porosity in 3D	

X-Ray computed tomography (CT or XCT)	particle size/shape, dimensional accuracy, internal flaws, porosity in 3D, volume fraction and inaccessible internal features	ASTM E1441, E1570
X-ray diffraction (XRD)	crystalline phase, microstructure	ASTM E1426, E2860
X-Ray photoelectron spectroscopy (XPS)	particle surface molecular/chemical composition	

1.3.3 Quasi-NDT of additive manufacturing Parts: micro/macro cell, micro-hardness, micro/nano-indentation

Quasi-NDT refers to those tests only cause minimal damage to the object. The damage is so small that it will not affect the integrity or functionality of components. Normally those techniques leave an extreme small foot print (smaller than 100 μm) on the sample surface, which can also be further removed if it could be an issue for the final product. These techniques also have advantage in determining spatial variation of properties on a single AM part (see Table 3).

Table 3 Quasi-NDT methods used for additive manufacturing components

Micro cell	electrochemical properties	
Micro hardness	Vickers & Knoop hardness	ASTM E384, ISO 6507-1, ISO 4545-1
Nano-indentation	elastic modulus & hardness	
Optical microscopy (OM)	grain structure, defects	ASTM E3

APPENDIX C PRINCIPLES OF TECHNOLOGY QUALIFICATION PROCESS

1 Process for technology qualification

Technology qualification is a systematic method to manage the uncertainties related to implementation of new technology. The objective of the method is to provide evidence that the technology will function within specific limits with an acceptable level of confidence. This appendix presents the motivation for using technology qualification (TQ) and gives an overview of DNV GL's technology qualification method.

1.1 Motivation for technology qualification

Implementation of new technology or technology with limited experience introduces uncertainties that imply risks for technology developers, financiers and end-users. As new technologies are usually only partly covered by existing standards, guidelines or recommendations, it can be difficult for the involved stakeholders to achieve a common understanding on whether or not a new technology is fit for purpose, and thereby to build the confidence necessary for deploying the new technology.

DNV's technology qualification method, described in DNVGL-RP-A203, provides a systematic way to manage the uncertainties related to deployment of new technologies or technologies with limited experience. The method is particularly valuable in cases where fitness for purpose cannot be relied on solely by demonstrating compliance with relevant standards, guidelines and recommendations. The method makes it possible to identify and analyse the risks associated with the new technology, and provide evidence that it is suitable for its intended use. Technology qualification can facilitate the deployment of new technology by reducing the risk for all stakeholders, including developers, manufacturers, financers and end-users.

1.2 Applying TQ principles for fitness for purpose of additive manufacturing products

DNV GL have established technology qualification process which describes TQ as the process of providing the evidence that a technology will function within specified operational limits with an acceptable level of confidence. The DNV GL document is written as a general procedure, and can therefore be used to qualify any new technology, as described next. DNVGL-RP-A203 adopts a work process (see Figure 1) that systematically reduces uncertainties, and thereby provides technical evidence that the technology works as intended.

The objective of the qualification work process is to provide a systematic approach to qualifying and documenting new technology; in this case, it is proposed that the TQ process is applied to the pressure equipment's metallic components produced by an AM process, through all stages of development, including the qualification and certification of the AM processes.

Detailed study on risk assessments on how AM processes will impact on the final performance of a component is required to conduct with collaboration from partners. Experience shows that technology qualification (TQ) process for approval of processes and components is elaborate, detailed and expensive but the principles of technology qualification can be used for technology assessment / pre-technology qualification for AM products before starting the approval of manufacturer process.

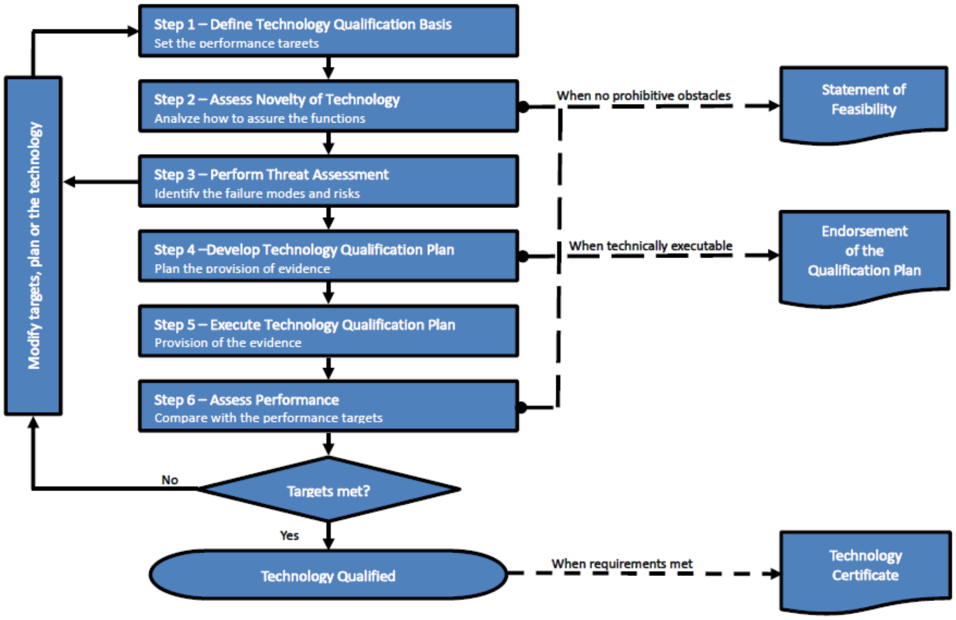


Figure 1 Steps in the basic technology qualification process from DNVGL-RP-A203

The TQ work process consists of distinct steps with milestones at which a certifying body may issue a statement or certificate providing the technology owner and users with an understanding of the level of qualification accomplished and the level of review performed. At the end of the process, a technology certificate may be issued by the certifying body, confirming compliance with the functional requirements and specified reliability targets. This qualification stands by the review of the evidence that adequately documents the TQ performance per the qualification basis and acceptance criteria.

1.3 Roles in technology qualification

Technology qualification can be applied by both technology developers and purchasers to assess the robustness of new technology. A technology developer may either use TQ internally to monitor the technology development process, or to demonstrate the maturity of the technology to potential investors or buyers. A purchaser will typically apply technology qualification to assess one or several alternative technologies considered for a development project. A TQ initiated by a purchaser will typically be conducted in cooperation with the technology supplier, to gain access to the information required for evaluating the technology. In cases where strict regulations on public procurements exist, it is important to ensure separation of the technology qualification of technologies and the procurement itself.

In any of the above mentioned cases, one or more third parties may be involved to facilitate the qualification process, to provide independent judgment, or for performing analysis and tests of the technology.

1.4 The six-step technology qualification process

DNV GL’s method for technology qualification is structured in a six-step process presented below:

Technology qualification basis

— Establishing a basis for the qualification by defining the technology to be qualified, its functions, its intended use, its operating environment, as well as the expectations to the technology and qualification targets.

Technology assessment

— Decomposing the technology into elements, categorizing the various elements by degree of novelty based on industry experience.

Threat assessment

— Assessing threats by identifying potential failure modes and failure mechanisms and estimating probabilities and consequences associated with each failure mode.

Establishing the qualification plan

— Developing a plan comprising the qualification activities necessary to address the identified risks.

Execution of the qualification plan

— Executing the activities specified in the technology qualification plan, collecting evidence through documented experience, numerical analyses and tests.

Performance assessment

— Assessing whether the evidence produced meets the requirements of the technology qualification basis. The flowchart in Figure 2 illustrates the process flow of the TQ process.

Figure 2 The six step technology qualification process

The output of each step in the process is used as input to the next step. The feedback loops indicates that it might be necessary to modify the original design or qualification requirements to incorporate newly identified threats or knowledge about the technology obtained from the qualification activities.

If the conclusion in the last step/performance assessment is that the technology has met all the requirements set in the qualification basis, the technology qualification has been successful. This may either mean that the technology is qualified and fit for purpose, or it can have reached some intermediate milestone in the development of the technology. This will depend on what type of requirements that were stated in the qualification basis.

1.5 Use of technology qualification in different project phases

Development of new technologies usually follows a stepwise process, starting with a business idea, proceeding through a number of preliminary development stages, before it can be considered fit for purpose and deployed. An example of a typical stepwise development process is illustrated in Figure 3.

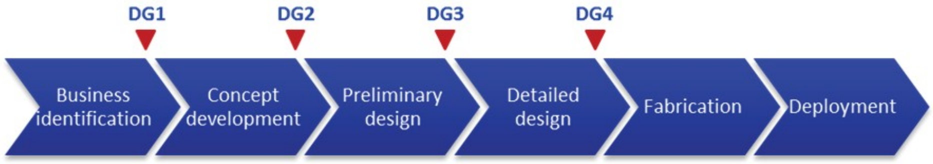


Figure 3 Example of a technology development process

To proceed to the next development phase, the technology usually has to pass decision gates (DG) where the continuation of the development process will be decided. The outcome will typically depend on the technology developer's ability to provide the evidence that the technology has reached a certain level of maturity and robustness. By applying technology qualification in the development process, the decision makers will have a better basis for decisions on whether or not to continue or deploy a new technology.

1.6 Input to the technology qualification process

The input to the technology qualification should comprise all information required to assess the novel elements of the technology to be qualified, including information on its intended usage and operating environment, as well as requirements on performance. This information shall be collected and structured in the first step of the technology qualification process, the qualification basis. The extent and the accuracy of this information will vary depending on the development stage of the technology considered.

1.7 Results from the technology qualification process

The results from the technology qualification process are the conclusions on whether the new technology meets the requirements defined in the qualification basis or not. These conclusions must be supported by evidence and documentation of all activities performed during the qualification process. This documentation shall provide sufficient transparency and traceability to allow independent assessment of the conclusions.

1.8 Qualification of complex processes and products

Qualification of a complex processes like AM process will normally require the different sub processes making up the overall process to be qualified separately before the combined system can be evaluated with respect to fitness for purpose. The requirements of each subsystem shall be consistent with the requirements specified for the overall system. The qualification of the combined system shall focus particularly on the interaction between the respective subsystems.

Typically, many of the subsystems will be well-known and covered by existing standards; hence it may seem unnecessary to perform a full qualification for these. It is, however, recommended to perform at least a simplified assessment for all subsystems, as the novel elements may have unforeseen effects on the presumably well-known elements.

1.9 TQ Process steps

Technology qualification is a systematic, stepwise and iterative process with the following six steps, per DNVGL-RP-A203:

Step 1 – define technology qualification basis

Step 2 – technology assessment

Step 3 – threat assessment

Step 4 – develop technology qualification plan (TQP)

Step 5 – technology qualification plan execution

Step 6 – performance assessment

Each of these steps is further explained below.

1.9.1 Step 1 – define technology qualification basis

This step defines the technology, its application, and the conditions under which the technology, or AM materials & components will operate. The purpose of the qualification basis is to provide a common set of requirements against which all qualification activities and decisions will be assessed. Through further qualification processes, these requirements are demonstrated to be fulfilled.

1.9.2 Step 2 – technology assessment

Technology assessment is used to determine what is the new technology, and what is prior art. DNVGL-RP-A203 adopts a technology categorization matrix as shown in Table 1.

This categorization indicates the following:

1) no new technical uncertainties (proven technology)
2) new technical uncertainties
3) new technical challenges
4) demanding new technical challenges.

“Application area” refers to the experience of the operating condition, or the environment, or the purpose for which the system, equipment or component shall be used.

Table 1 Technology categorization matrix from DNVGL-RP-A203.

Application area	*Degree of novelty of technology (i.e., technology maturity)*		
	Proven	*Limited field history*	*New or unproven*
Known	1	2	3
Limited knowledge	2	3	4
New	3	4	4

“Novelty of the technology” refers to the technology itself. A change in any of the elements of existing technology (parts, functions, processes, subsystems) will lead to increased uncertainty resulting in selecting the technology novelty “Limited Field History” or “New or Unproven”. The change may be related to hardware or software components of the technology. Change may be related to technology elements such as new component geometry, new AM process and AM production equipment, AM in-situ monitoring system interfaces, and increased reliability requirements.

Technology novelty category “1” is proven technology, where proven methods for tests, calculations, and analysis can be used to document the operating margins. These elements should be handled through the regular design process, implementing adequate QA/QC to ensure sound engineering. Elements categorized as novel technology (categories 2, 3, and 4) shall proceed to the next step of TQ for further assessment. AM of pressure equipment brings new technical uncertainties, and based on the new and demanding technical challenges, would be at least a category 3 or 4, considering the current AM development status review.

1.9.3 Step 3 – threat assessment

This step identifies relevant failure modes with underlying causes and failure mechanisms for AM components, and to assess the associated risks. The report from the threat assessment contains a register of all identified risks and identifies those to be addressed by the continued TQ. For each risk determined not to be addressed by the TQ, it also provides either reference to acceptance criteria from referenced standards or practices that are considered adequate for that risk, or reference to evidence substantiating that the risk has been adequately accounted for.

When it is confirmed that the technology assessment and the threat assessment have no prohibitive obstacles, a formal statement of feasibility can be issued. Examples of associated risks that AM pressure equipment can be exposed to include, but are not limited to, the following:

- material heterogeneity and associated mechanical
- properties in longitudinal and transverse orientation;
- material property variations from one build to another,
- or even one location to another;
- property degradation caused by internal general
- porosity level, porosity size and distribution;
- property variation caused by internal residual stresses;
- localized corrosion issues due to element segregation,
- and non-homogeneous microstructures.

1.9.4 Step 4 – develop technology qualification plan (TQP)

Based on the risks identified in the Threat Assessment, relevant qualification methods are customized and documented to mitigate risks to an acceptable level under the defined conditions. The purpose of technology qualification planning is to describe how qualification evidence will be provided. Suitable qualification methods are identified. The qualification plan explains the reasoning that justifies the selected qualification activities by:

- Identifying the evidence that the plan intends to produce.
- Tracing this evidence back to claims made of functionality and performance and the failure modes they intend to mitigate and the required failure margins.
- Entailing an unambiguous description of the acceptance criteria to determine if the qualification activities were successful in providing the required evidence.

When it is confirmed that the TQP is technically executable, a formal Endorsement of the qualification plan can be issued.

Specifically, for AM processes, the qualification methods can involve in-situ processes, with advanced sensors to monitor parameters, computer modelling of processes, microstructures, and properties, the assessment of essential variables, customized component pressure testing, etc., and any other methods to test AM-related properties of the AM component.

1.9.5 Step 5 – technology qualification plan execution

In this step, the details described in the TQP are executed in accordance with how the technology is designed, manufactured, and tested, to provide qualifying evidence.

These activities include:

- providing technical expertise in failure mode identification and risk ranking
- technical analyses and studies
- laboratory testing or computer analyses
- development of models for failure mechanisms
- development of plans and specifications for analyses and testing
- risk and reliability analyses.

1.9.6 Step 6 – performance assessment

In this step, the results of the qualification activities are evaluated against the technology qualification basis and the acceptance criteria in the TQP. This is done to ensure that all relevant failure mechanisms have been addressed and risks reduced to an acceptable level. With this information, a decision is then made to approve the system for implementation, re-design the system for further qualification, or cancel deployment of the technology. A successful performance assessment implies that the TQ has been successfully completed and hence that the basic claim is proven true for the cases covered by the qualification.

Upon completion of the technology qualification process, and when requirements are met, a formal *Technology Certificate* can be issued.

CHANGES - HISTORIC

There are currently no historical changes for this document.

About DNV GL
Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification, technical assurance, software and independent expert advisory services to the maritime, oil & gas and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our experts are dedicated to helping our customers make the world safer, smarter and greener.

SAFER, SMARTER, GREENER