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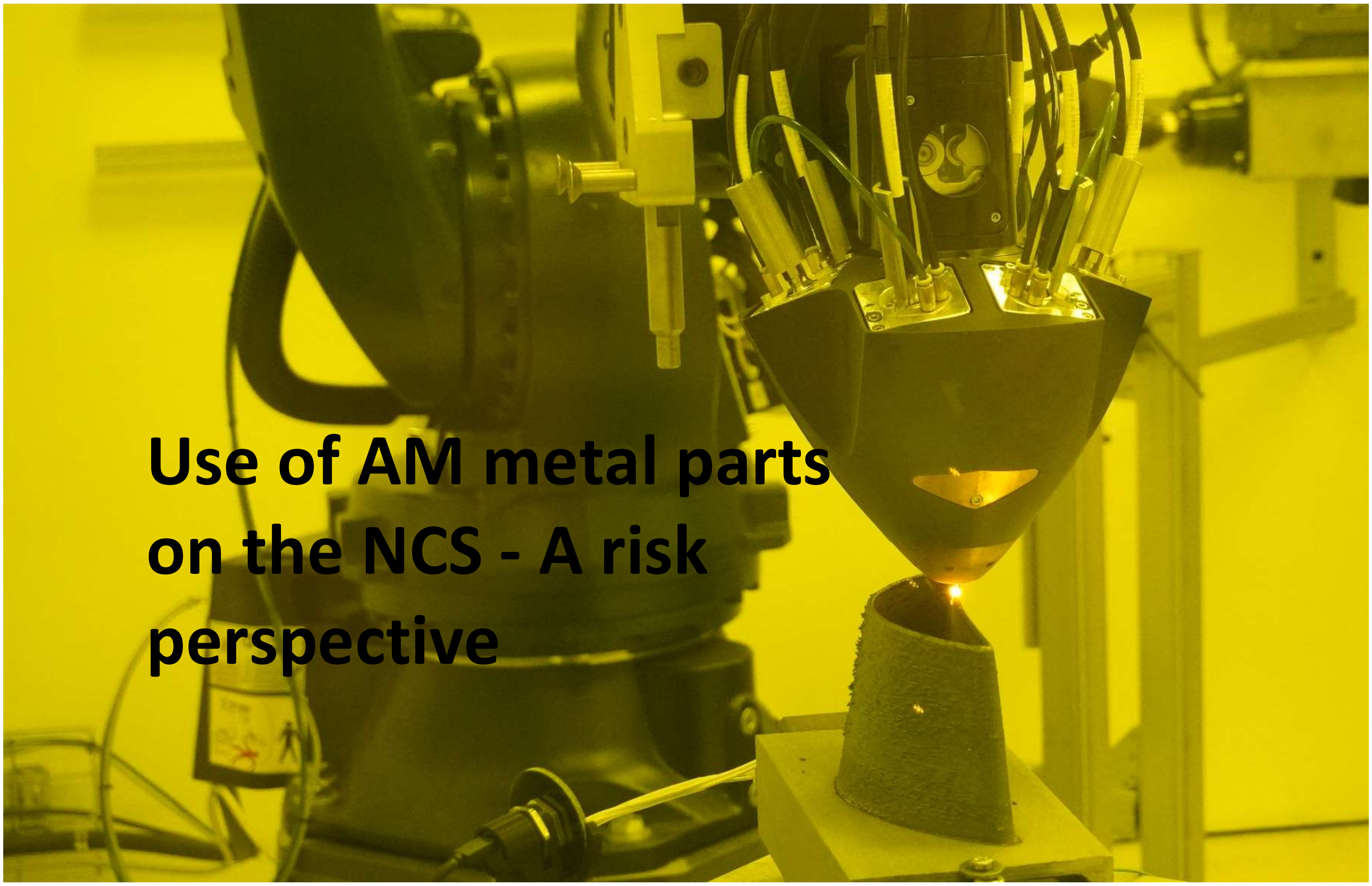

Use of AM metal parts on the NCS - A risk perspective

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Report

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SUMMARY

Additive manufacturing (AM) will just like any other manufacturing method, generate specific material properties. The AM methods are characterised by thermal cycles and high cooling rates that greatly impact the as-built microstructure and surface, often requiring subsequent heat treatment and machining.

Incorporating production methods that have a limited track record among end-users, procurement, certifying bodies and manufacturers, requires understanding of the process to ensure adequate properties. This report encompasses a literature review on the metallurgy behind metals produced by AM and a questionnaire that assesses viewpoints among some major operators on the Norwegian continental shelf (NCS). The literature review provides a basis for a subsequent discussion on the risks of employing AM material offshore. This discussion details current efforts within standardization and problems that may arise when supply-chains are to be established.

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1 Intro

Report is written for **Havindustritilsynet, The Norwegian Ocean Industry Authority** as a response to the following request:

> A study will be conducted to evaluate the risks and challenges associated with the use of additively manufactured metallic parts in the oil and gas industry. The following topics are to be addressed in the study:
>
> - Status and potential in the area
> - Standards and guidelines for qualification and use
> - Methods, materials, and metallurgy
> - Assess whether there is a higher risk of various degradation/failure mechanisms in additively manufactured parts
> - Evaluation of risks and challenges related to the use of the parts in the industry
> - Collect information from operators on the Norwegian continental shelf on how they assess the risks of using additively manufactured parts, as well as an overview of how widespread the use of such parts are in the industry and the qualification regime for these (questionnaire)

The work in this report was performed between April 2024 to December 2024 and the validity after these dates will be altered due to the rapid development within Additive Manufacturing (AM) technology. All figures except those specifically made for this report, are from open access sources and have been cited.

The questionnaire we sent out to the major operators on the NCS should be used to understand the general viewpoints in 2024 from these individuals working for these operators.

When engineers refer to materials it is not always understood that the production method leaves a great impact on the final properties. This is very important when it comes to AM. AM is a set of methods that all produce different thermal cycles and generate different microstructures. At present, AM has the potential of reducing delivery times significantly, but also poses the risk of producing microstructures that are different from traditional methods. This report will try to describe the risks and changes that occur when AM is used as an alternative to such traditional methods of manufacturing.

2 List of abbreviations used:

AM: Additive manufacturing
AMC: Additive manufacturing category
AMSL: Additive manufacturing specification level
BPQ: Build process qualification
BPQR: Build process qualification record
CMT: Cold metal transfer
COF: Consequence of failure
CP: Commercially pure
CT: Computer tomography
DED: Directed energy deposition
DLP: Digital light processing
DSSs: Duplex stainless steels
EB: Electron beam (used e.g. as PBF-EB or DED-EB)
EDS: Energy dispersive spectroscopy
EoF: Elongation of failure
FAT: Factory acceptance test
FDM: Fused deposition modelling
GMAW: Gas metal arc welding
Havtil: Havindustritilsynet
HIP: Hot isostatic pressing
LB: Laser beam (used e.g. as PBF-LB or DED-LB)
LOF: Lack of fusion
LOM: Light optical microscope/microscopy
MDS: Material data sheet
NCS: Norwegian continental shelf
NDT: Non-destructive testing
PBF: Powder bed fusion
POF: Probability of failure
PPS: Part production specification
PQ: Part qualification
PQR: Part qualification record
PREN: Pitting resistance equivalent number
PWHT: Post weld heat treatment
SEM: Scanning electron microscope/microscopy
SLA: Stereolithography
SSTR: Solid solution temperature regions
STA: Solution treatment and aging
UTS: Ultimate tensile strength

3 Standards and guidelines

Standards are established norms or requirements for in this case methods and materials. In this report API, DNV, ISO and ASTM are discussed and while definition of terms, classification of components, test methods etc. can vary between standards, the differences are small today. Some differences are pointed out and discussed below. The AM standards are of course new compared to casting and forging standards and therefore inherit a lot from these standards. AM methods often generate a different microstructure compared to traditional methods due to the differences in heat history etc. and when taking traditional materials and forcing them into a new production method some challenges occur. The standard organization shall have this knowledge and develop them for these differences.

The standards have different quality levels detailing the category or criticality of the product. Risk increases criticality, and high-risk parts will typically be certified with categories that require more rigorous certification and testing requirements.

In DNV-ST-B203 there have been established four different additive manufacturing categories (AMC). API has a similar system for categorizing components.

Additive manufacturing category	**Requirements**	**Typical deliveries**
AMC 0	Part built by a qualified facility	• Part(s) with verifiable traceability information
AMC 1	• Part built using a qualified build process by qualified manufacturer • Simplified quality control of delivered parts • Other requirements as agreed with purchaser	• Part(s) with verifiable traceability information • Details of PPS and BPQ or BPQR • Testing and inspection reports
AMC 2 and 3	• Part built using a qualified build process and qualified part production specification by a qualified manufacturer • Medium and higher quality control of delivered parts • Other requirements as agreed with purchaser	• Part(s) with verifiable traceability information • Details of BPQ or BPQR • Details of PSS and PQ or PQR • Testing and inspection reports

The steps that are covered in these AM standards are, all the way from feedstock production through design and preparing for production to production and quality assurance of the parts. For powder-based processes the regime for reuse and quality control of the powder is well defined since the powder quality has a big impact on end quality.

Generally, the API 20S standard has a similar, and in some areas, more comprehensive test-regime than the DNV standard while the DNV in some areas have different requirements.

The current standards in additive manufacturing for the petroleum and natural gas industries are notably conservative, emphasizing stringent quality measurement and control. Given the novelty and inherent uncertainties of these production methods, such rigorous material testing is justifiable for safety reasons. However, this thorough testing process also results in higher costs for manufacturing AM parts.

It is crucial that both the customer/end-user and the manufacturer develop a thorough understanding of the issues that can occur with AM manufactured parts like the industry has done with all other manufacturing methods. A lack of knowledge in either ordering competence end or the production process end can lead to significant problems. Therefore, the standards are essential as they help both parties grasp the extensive efforts required for quality checks and management.

3.1 ISO standards relating to AM

In 2011 ISO and ASTM signed an agreement to cooperate on the development of AM standards. This cooperation was planned to increase the market relevance of ISO and ASTM standards and eliminate duplication of standards. The ISO and ASTM standards cover a broader range of industries compared to API.

3.2 API standards relating to AM

API standards refer to ASTM or ISO standards for all steps in the process from feedstock to final testing. API 20S "Additively Manufactured Metallic Components for Use in the Petroleum and Natural Gas Industries" is using an Additive Manufacturing Specification Level (AMSL) to define levels of quality assurance in each step. It includes requirements for the qualification of the manufacturing process, production, marking, and documentation of metallic components produced through additive manufacturing. The strictest level will greatly impact the cost of production through AM due to the number of tests needed to comply. The goal of 20S is to enhance component design, cut down lead times, and increase efficiency by applying what they believe is the correct safety and efficiency requirements.

3.3 ISO/ASTM International standards related to AM:

- ISO/ASTM 52900, Additive manufacturing — General principles — Fundamentals and vocabulary
- ASTM F3592-23 Standard Guide for Additive Manufacturing of Metals – Powder Bed Fusion – Guidelines for Feedstock Re-use and Sampling Strategies
- ISO/ASTM 52928:2024 Additive manufacturing of metals - Feedstock materials - Powder life cycle management
- ISO/ASTM 52935:2023 Additive manufacturing of metals - Qualification principles - Qualification of coordination personnel
- ISO/ASTM 52920:2023 Additive manufacturing - Qualification principles - Requirements for industrial additive manufacturing processes and production sites
- ISO/ASTM 52909:2024 Additive manufacturing of metals - Finished part properties - Orientation and location dependence of mechanical properties for metal parts
- ISO/ASTM 52908:2023 Additive manufacturing of metals - Finished Part properties - Post-processing, inspection and testing of parts produced by powder bed fusion
- ISO/ASTM 52926-1:2023 Additive Manufacturing of metals - Qualification principles - Part 1: General qualification of operators
- ISO/ASTM 52926-2:2023 Additive Manufacturing of metals - Qualification principles - Part 2: Qualification of operators for PBF-LB
- ISO/ASTM 52907:2020 Additive manufacturing - Feedstock materials - Methods to characterize metal powders (ISO/ASTM 52907:2019)
- ISO/ASTM 52904:2019 Additive manufacturing — Process characteristics and performance — Practice for metal powder bed fusion process to meet critical applications

- ISO/ASTM 52931:2023 Additive manufacturing of metals — Environment, health and safety — General principles for use of metallic materials
- ISO/ASTM PWI 52954-1, Additive manufacturing - Qualification principles - Part 1: Common failure modes used for risk mapping
- **The list above does not include all standards related to AM**

For test methods, ASTM alone have 16 standards as of 2024-06-03
In total for AM the list includes 68 standards on topics divided into: **Applications, Design, materials and Processes, Terminology, Test Methods.**

4 Additive Manufacturing methods

Terminology is in accordance with ISO/ASTM 52900.

Indirect use of AM will not be discussed in this report. An example would be the making of sand moulds for conventional casting with binder jetting. Note that the method of building a sand-casting mould with AM to use in ordinary casting manufacturing is a very fast and efficient method of making large parts by indirect use of AM. The methods listed below can be used for a variety of materials but in this report only metals are discussed.

1. **Metal Powder Bed Fusion (PBF)**
    1. Powder Based Fusion-Laser beam (PBF-LB): This method uses a laser to selectively melt metal powder layer by layer, creating complex 3D structures.
    2. Powder Based Fusion-Electron beam (PBF-EB): PBF-EB uses an electron beam to melt metal powder. It's similar to PBF-LB but operates in a vacuum.
2. **Directed Energy Deposition (DED)**: In DED, material is deposited layer by layer using a focused energy source (such as a laser, arc or electron beam). It is used for large-scale parts and repair applications.
    1. DED-LB: Utilizes one or more lasers for melting. Feedstock supplied as powder or wire
    2. DED-Arc: Also known as wire arc additive manufacturing (WAAM). Utilizes an electric arc to melt feedstock, typically supplied as wire.
3. **Binder jetting**: In this method, a liquid binder is selectively deposited onto a powder bed, binding the particles together. It's suitable for ceramics, metals, and sand-casting moulds.

4. **Material extrusion (MEX, commonly known as fused deposition modelling, FDM)**: FDM involves extruding heated material (usually plastic filament) through a nozzle to build up layers. It is commonly used in desktop 3D printers.
5. **Material jetting:** A process in which droplets of feedstock material are selectively deposited
6. **Sheet lamination**: In sheet lamination, layers of material (usually paper or plastic) are bonded together using heat or adhesive. It is less common but has applications in rapid prototyping.
7. **VAT photopolymerization**: This includes SLA (Stereolithography) and Digital Light Processing (DLP), where liquid resin is cured by light exposure. It's mainly used for detailed and complex parts.

Each method may have sub-methods.

The AM methods discussed in this report will be the methods that are relevant for, and at this time used to manufacture metallic components on the NCS. Those include PBF, DED, and to some extent binder jetting.

All methods listed above could be applied for different purposes on the NCS. Some methods are more likely to be used due to the materials used and the size of components. For smaller products in metal, PBF-LB and PBF-EB are common methods for e.g. titanium and stainless steels. For larger components: Laser, or wire arc heat sources for DED are common methods.

- Sheet lamination has yet to become a widely implemented method and is not discussed in this report.
- Polymer AM methods are not included in this report.

4.1 AM Methods

Additive manufacturing is a rapidly expanding field. Sales of AM systems for metal parts increased by 24.4% in 2023, with an estimated 3793 systems sold [1].

When AM Power conducted an overview of different AM technologies, they identified a total of 149 suppliers of AM production technologies on the global market. With so many companies developing and selling machines using different technologies, the expected material properties can vary significantly. This diversity is beneficial for technological development but also introduces risks. The presence of numerous similar and evolving AM technologies necessitates rigorous testing to ensure reliable end results.

The most used methods for producing metal parts, which are now and can be used on the Norwegian Continental Shelf (NCS), are presented below.

4.1.1 Powder bed fusion (PBF)

A process in which thermal energy selectively fuses regions of a powder bed to form an object. The process works by melting fine metal powder in a powder bed, layer by layer. A laser beam (LB) or electron beam (EB) supplies the necessary energy, and the system operates in a protective atmosphere of nitrogen, argon or vacuum in the EB case. The method has been on the market for a long time, with many users. As a result, it is one of the most production robust AM technologies on the market. Today the most advanced machines spread the powder in layer thicknesses ranging from 5 up to 200 µm, while the most common is around 30-60 µm. Selection of layer thickness is a trade-off between build rate, density and tolerance.

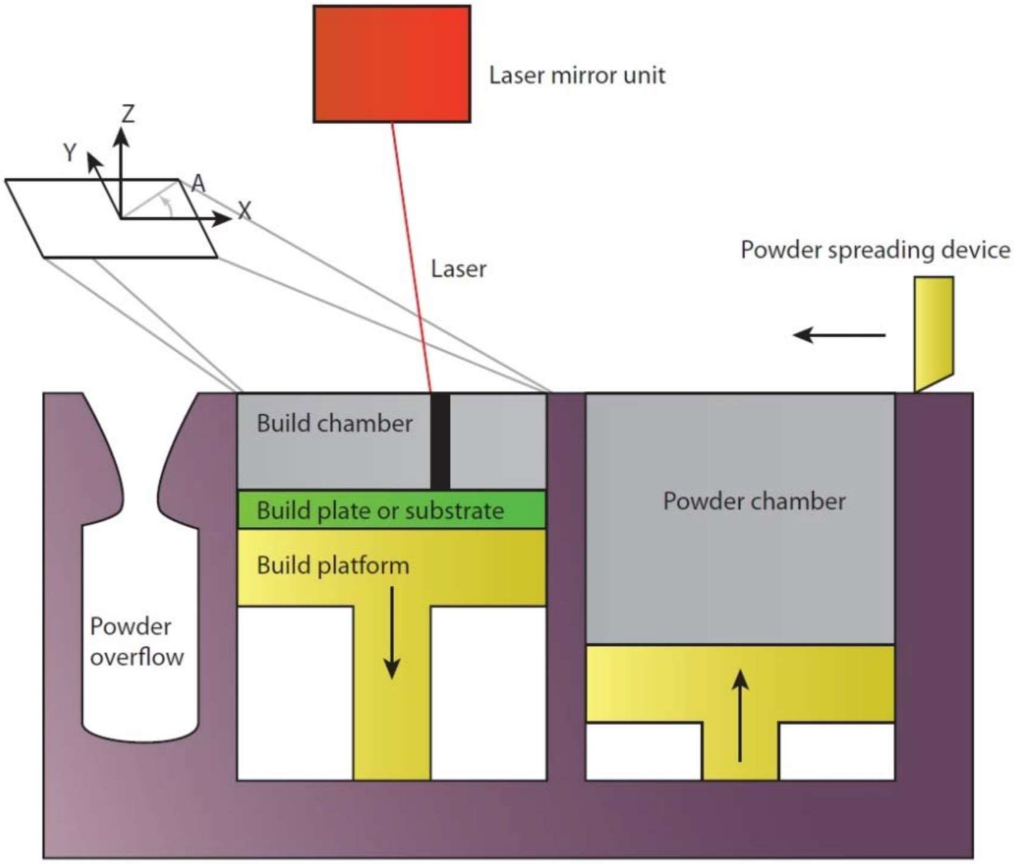

Figure 1: Powder Bed Fusion laser machine overview. Electron beam will have a similar setup

Powder Bed Fusion process steps:

1. The powder chamber moves up one step
2. The spreading device moves powder from the powder chamber to the build chamber
3. The Laser/Electron beam selectively scan powder to fuse it with previous layers
4. Build chamber moves one layer down
5. Process start all over again

Since the powder bed is held at a relatively low temperature for laser processes, stresses can be induced in parts. Supports are therefore required as well as a strong and stiff build plate to prevent thermal distortion of build parts. The high temperature gradient and the very rapid heating and cooling (10^6-10^8 K/s) influence the material, and the amount of heat induces stress. Heat treatments are often required to normalize the properties.

A few suppliers have a technology where a combination of milling and PBF is done in one machine. This allows for less post processing and build geometries that would be difficult to produce with PBF alone. An inner geometry that would be impossible to machine after a finished PBF process can with this combined solution, be machined during the build process.

Several AM processes allow for hybrid manufacturing. Here a combination of methods are used to finalize a geometry. This can be via building on a semi-finished part, using different processes and tools during the build, or the semi-finished part being moved in between production processes.

4.1.2 Powder Bed Fusion using Electron Beam (PBF-EB)

Metal powders are consolidated into a solid using an electron beam as the heat source, similar to PBF-LB. PBF-EB technology manufactures parts by melting a metal powder layer-by-layer with an electron beam in a heated high vacuum build chamber. The first supplier that was selling machines with this technology was Arcam AB. Now with the patents being out of age new suppliers are on the market. Electromagnetic coils provide control of the electron beam-size and movement. The beam can allow several active melt pools to be maintained simultaneously. For each layer in the build the electron beam heats the entire powder bed to a material specific temperature before it starts to selectively fuse material.

Laser vs Electron beam for PBF

One advantage is that PBF-EB is a faster AM process compared to PBF-LBs, since it creates components with low thermal stresses and good mechanical properties. Surface finishing and post heat processing may be required if component specification requires high fracture toughness and/or fatigue resistance. The lower thermal stress is possible because the powder in the build chamber is kept relatively hot, typically between 700 and 1000°C. This leads to lower induced stresses in the parts because of smaller amounts of cooling during the build cycle. It has been shown that Ti-6Al-4V processed using the PBF-EB process can have comparable ultimate tensile strength and elongation properties to wrought material. Another advantage of the PBF-EB process is that it is faster than laser-based powder bed systems. However, the surface roughness for PBF-EB parts is slightly higher than for PBF-LB. In the PBF-EB process, the unfused powder will be lightly sintered due to the high temperature. During the building process, the lightly sintered powder act as support for the succeeding layers, and there is less need for specially designed support structure, which is needed in the Laser Powder Bed Fusion process.

PBF-EB has a greater design freedom compared to PBF-LB since it needs less or no support structure.

4.1.3 Directed Energy Deposition (DED)

A process where focused thermal energy is used to fuse metal powder or wire feedstock by melting as it is being deposited to form an object. The energy in the form of laser, plasma, arc or pure particle impact energy is directed onto an area, while powder or wire is simultaneously fed and melted onto the underlaying material. The wire-based techniques share many similarities with welding.

One major difference to PBF, is that some DED techniques can allow reorientation of the part during the build process by use of a manipulator (tilt- and rotation table). This gives the ability to build in different directions relative to the substrate or build plate, thereby minimizing the need for support structure.

This process can also be used to repair or add additional material to an existing component and can also be used for multi-material applications. This enables a low-cost base material and an advanced surface. A typical DED machine consists of a deposition or build head mounted on a multi axis arm, which deposits melted material onto the specified surface.

4.1.4 Directed Energy Deposition – Laser based

DED-LB utilize laser for melting. Feedstock can be in the shape of both powder and wire. Most DED-LB techniques use one or more laser beams to create a melt pool in the build surface, into which feedstock is added. Laser as a heat source will typically enable smaller melt pools with lower heat input, less penetration and higher resolution than arc-based processes, see Section 4.1.5. One main advantage of employing laser beams is that the process is very clean, typically without fumes or spatter, and the wide range of available laser types enables freedom to optimize the process.

With laser-based DED, wire feedstock can either be fed from the side (lateral wire feed) or coaxially. Lateral wire feed makes the process direction-dependent, and the deposition paths must typically be planned according to the wire feed direction. Coaxial wire feed has the advantage of being direction-independent in the XY-plane. This is typically achieved by using optics to create a laser cone from splitting a single, powerful fibre laser, and feeding wire in the central axis of the cone. Precitec’s deposition head utilises this principle. Another solution is to employ several lasers arranged in a cone shape around the wire feeding central axis. Meltio and Oscar PLT both provide deposition heads that employ this solution. There are also coaxial DED-LB setups that use a powerful fibre laser in the central axis, with lateral, symmetric wire feed of several wires to make the system coaxial. The disadvantage with coaxial wire feed is that the process becomes sensitive to layer height deviations.

4.1.5 Arc based Directed Energy Deposition

DED-Arc uses welding technology to create an electric arc which supplies heat for melting. Tungsten electrodes have been used with lateral wire feed, but the main techniques applied in AM are variants of gas metal arc welding (GMAW), commonly known as wire arc additive manufacturing (WAAM). This is well-established technology, which is relatively easy to implement on a robot arm for automation. Since GMAW equipment is coaxial by nature, this equipment gives freedom of movement in the XY-plane. In addition, it is less sensitive to layer height deviations than the coaxial DED-LB systems. The cold metal transfer (CMT) process from Fronius is often employed for AM since it is capable of high deposition rates with lower heat input than conventional GMAW equipment.

DED-Arc equipment is often economical to procure and set up and can provide high deposition rates. The main challenge is that the high heat input can make heat management challenging. This is usually resolved by introducing an idle time to allow the part to cool between deposition of beads, but this reduces productivity considerably. The detail resolution is much lower than with most other AM processes, making DED-Arc a preferable technique for bigger parts where high deposition rates is required, and where the part size enables sufficient cooling to avoid excessive idle time.

4.1.6 Cold Spray

Cold spray is an additive technique where metal powder is accelerated towards a surface with sufficient energy to fuse the particles by cold, plastic deformation [2]. This process is best suited for softer materials and is often employed with materials that are difficult to manufacture by fusion-based AM processes like aluminium, copper and magnesium alloys. Cold spray does not melt metals and the materials are thereby not affected by heat-related distortion, and parts do not need to be manufactured in an inert gas which enables building of large structures [3].

A key advantage of cold spray is that there is no heat input, and thereby no heat affected zone. This is significant for aluminium alloys, since the allowable utilisation of a T6 aluminium grade, e.g. 6062 T6, will be 50 % in the heat affected zone, which leads to challenges with global structural ductility and a need for bigger element cross sections. Repair of corrosion damaged structures, e.g. helidecks, is a highly relevant use case for cold spray on the NCS.

The cold spray process has some limitations. The process is sensitive to angled surfaces, i.e. it requires the material to be sprayed onto a perpendicular surface. In addition, it is sensitive to process parameters, and will typically not produce a very clean microstructure, so both oxide inclusions and porosities are common [4].

5 Offshore relevant materials

The more common metals or alloys available for AM are:

- Stainless steel alloys
- Steel alloys
- Titanium alloys
- Aluminium alloys
- Copper alloys
- Cobalt Chrome alloys
- Nickel Alloys
- Gold
- Silver
- Platinum
- Palladium alloys

For usage on the NCS the materials that are relevant to use with the available AM methods would include:

- Stainless steel alloys
- Steel alloys
- Titanium alloys
- Nickel Alloys

5.1 Steel alloys

Several low-alloyed steels can be manufactured by AM. This wide range of materials can span from simple carbon steels to quenched and tempered and even hardened steels.

5.2 Stainless steel alloys

5.2.1 304

AISI 304 is an austenitic chromium-nickel steel with improved machinability. The grade is general purpose stainless steel with good resistance to atmospheric corrosion and many organic and inorganic chemicals. Due to low usage on the NCS this alloy will not be further discussed.

5.2.2 316L

AISI 316L is one of the most used corrosion resistant alloys in AM. It is also a common material on the NCS, especially for utility systems. A considerable advantage of 316L is its availability and ease of fabrication. The main challenge with 316L is its marginal corrosion resistance in marine atmosphere, where a lean duplex would provide an advantage of both strength and corrosion resistance.

5.2.3 Duplex

Duplex alloys (22Cr) are a workhorse on the NCS due to their combination of corrosion resistance, strength and toughness [5], [6]. Duplex alloys provide good corrosion resistance in marine atmosphere, which has led to 2205 duplex becoming the main material for process systems on the NCS. Its typical composition is 22 % Cr, 5 % Ni and 3 % Mo.

5.2.4 Super Duplex

Super duplex alloys (25Cr) have elevated chromium, nickel and molybdenum content, where the higher chromium and molybdenum content makes them corrosion resistant in seawater. Typical composition will be 25 % Cr, 7 % Ni and 4 % Mo. Due to their compositions; super duplex grades are stronger than standard 22Cr duplex. However, the alloy content also makes the super duplex grades more susceptible to precipitation of detrimental microstructural constituents like sigma and chi phase.

5.2.5 6Mo

6Mo super austenitic steel combines moderate tensile strength and high ductility with corrosion resistance in seawater. As an austenitic grade, it provides excellent toughness but can precipitate sigma phase during processing. 6Mo is often used for tubing in marine atmosphere since it can be used without surface protection and is relatively easy to cold-bend. 6Mo has been used in process systems, but duplex grades are usually favoured due to their increased resistance to stress corrosion cracking as well as their higher strength.

5.2.6 17-4 PH

17-4 PH is a grade of martensitic precipitation hardened stainless steel that finds use in applications that require high strength and moderate corrosion resistance. It is often used in drilling equipment and subsea installations due to its high strength, but since it is not corrosion resistant in marine atmosphere, it is not used much topside.

5.3 Titanium alloys

Titanium is an expensive material that provides very high corrosion resistance. Its main use is for applications where it is in contact with seawater, like firewater, seawater heat exchangers, etc. It can maintain its corrosion resistance at higher temperatures than super duplex and 6Mo.

Titanium can be classified into four broad groups depending on alloying content and its effect on phase formation. Depending on the composition of β-stabilizing elements (Mo, V, Nb, Fe, Cr, Mn, Si and Cu) and α-stabilizing elements (Al), both α-alloys, β-alloys and α+β alloys can be manufactured. In addition, commercially pure titanium, such as Grade 2 is widely used and often classified as an α-alloy. The α+β alloys consume much of the titanium market, where over 50% consists of Ti-6Al-4V (grade 5) [7]. Through control of the alpha or beta phase fractions, Ti-6Al-4V can be engineered to achieve the desired mechanical properties and corrosion resistance.

5.3.1 Ti-6Al-4V (grade 5)

Ti-6Al-4V is an α-β alloy that has been extensively tested for AM. It is often used when both high strength and good corrosion resistance is required. The alloy is usually annealed to remove dislocations, internal stresses and a martensitic phase that is prone to form through AM, see section 6.5.1.

5.3.2 Commercially pure (CP) titanium (Grade 2)

Commercially pure titanium is characterized by a composition of >99% Ti, high ductility and excellent corrosion resistance. Solid solution interstitial strengthening by additions of nitrogen and oxygen provides yield strength in the range 275-450 MPa.

5.4 Nickel-based superalloys

There exists a wide range of nickel-based alloys. Discussed below, are two of the most used nickel-based alloys in the offshore industry. The term “superalloy” is used as a designation for alloys that achieve excellent creep-resistance and strength through the precipitation of an intermetallic $Ni_3(Al,Ti)$ phase (γ’). Empirically the content of γ’ has been closely tied to the weldability and printability of the superalloys. Furthermore, there are subclassifications of the superalloys depending on composition, namely nickel-iron superalloys, nickel-based superalloys and cobalt-based superalloys. Among these, the nickel-based superalloys are widely used and extensively reported on in AM-oriented literature. They are characterized by a composition of >50wt.% Ni [8].

5.4.1 Alloy 625

Possibly the most used nickel-based superalloy in the gas and oil industry, nickel-based superalloy 625 offers excellent corrosion resistance for high temperature applications. The localized corrosion resistance is primarily linked to additions of 20-23wt.% chromium and 8-10wt.% molybdenum, which makes the material an excellent choice for offshore applications. Use cases where material properties need to remain in high-temperature environments are where nickel-based superalloys excel.

5.4.2 Alloy 718

Nickel-based superalloy 718 is a corrosion resistant nickel-based superalloy that achieves high strength through heat treatment that involves age-hardening and precipitation strengthening. Alloy 718 possesses a higher tensile strength than that of 625, making it better suited for applications where high loads are involved.

6 Microstructures and material properties

The microstructure and material properties of an AM-produced part depend on the material grade and AM process. While an abundance of research aims at characterizing mechanical properties, less has been devoted to corrosion resistance. The latter is of a higher importance in many offshore applications.

Section 6 aims to outline the most important characteristics of offshore-applicable materials manufactured by different AM processes. It starts with section 6.1, which provides general insight into the microstructure of parts produced by AM. Problems of texture and anisotropy are discussed here. Section 6.2 broadly introduces the effect of heat treatment strategies in AM, with further details for materials specific to offshore applications provided in subsequent Sections 6.3-6.6. In these sections the reader should be aware that all AM processes produce different microstructures that depend on the specific alloys. The intention of this report is to highlight important trends and identify possible risks in using AM materials for offshore applications. Properties of materials in the as-built state differ from the properties post heat-treatment, and this is pointed out with suggestions of appropriate heat treatment. Risks are indirectly identified by comparing the properties of traditionally manufactured and AM components, and by highlighting uncertainties due to limited available scientific literature. For all materials, the discussion of properties is primarily restricted to PBF and DED as an overwhelming number of studies pivots around these two manufacturing techniques. Important to note is that all production methods will generate specific material properties, which is also true for the different AM methods.

6.1 Texture and columnar vs. equiaxed growth

Standards such as DNV-ST-B203 and API 20S have been developed to outline the different testing requirements of parts produced by AM. API 20S specifically addresses use in the petroleum and gas industries. Both standards address the need to perform tensile tests in different orientations, but DNV-ST-B203 provides a wider range of methodologies for tensile testing. Typically, tensile tests are required to be performed along at least two axes and at different build heights to ensure process quality. Furthermore, DED requires one test to be done parallel to the deposition track and build direction. These rigorous testing requirements are necessary due to the inherent material anisotropy resulting from AM processes. DNV ST-B203 explicitly cautions the application of AM to parts that are expected to hold isotropic properties.

The solidification theory presented below helps explain how AM parts develop anisotropic properties due to crystallographic texture. Furthermore, changes in solidification parameters with deposition height may induce different phases and morphologies depending on the material, also causing anisotropy. Examples from literature are used to consolidate the importance of this theory when deciding to utilize AM.

Crystallographic texture in material science refers to the tendency grains have to distribute themselves in certain crystallographic orientations. A material containing no such tendency and random grain orientation, is said to have no texture. Several processes may induce such distributions, including annealing and forming. However, AM is particularly well known to create these inherent solidification textures that may cause anisotropic properties. The evolution of texture in an AM-fabricated sample can be explained by the columnar dendritic growth that occurs during deposition. Typically solidification maps are used to show this, where a parameter for the solidification growth rate (R) is plotted against the thermal gradient (G) to predict the microstructural evolution, see Figure 2. The growth rate is the speed at which the solid front grows in the melt pool.

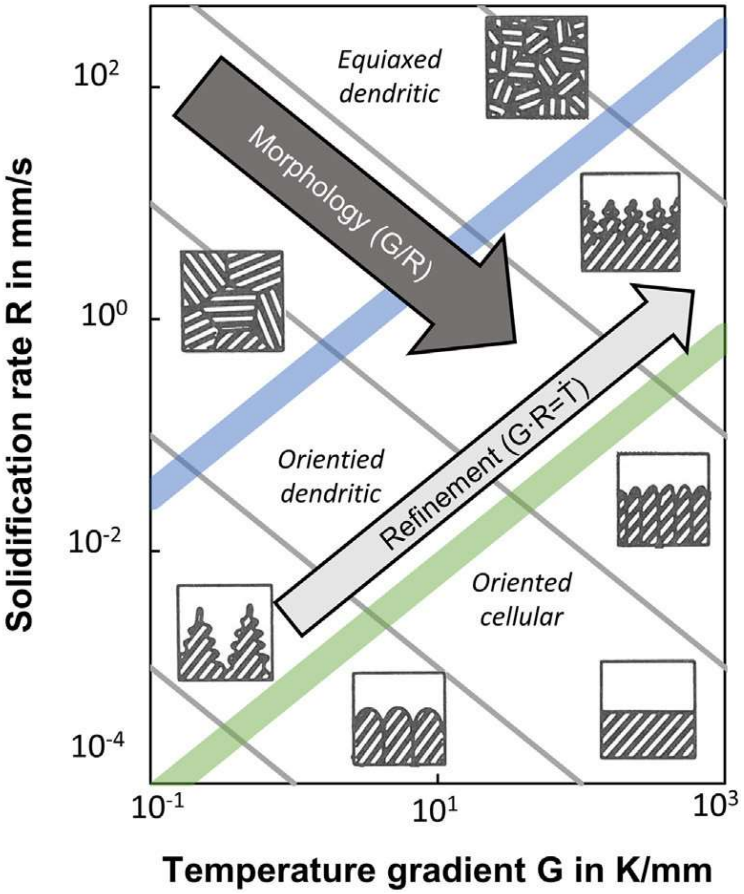

Figure 2: Schematic of a solidification map for different modes of microstructural growth/morphology [9]

Due to the rapid solidification rate and high thermal gradients in AM processes, planar and columnar dendritic structures will grow epitaxially parallel to the thermal gradient, i.e. along the build direction of the part. As layers are being deposited, stored energy causes the thermal gradient to decrease with the number of deposited layers. This can affect microstructure and tensile properties along the build height. Furthermore, the geometry of a part affects thermal cycles due to the available area for conduction. Examples from literature are listed below.

- A DED produced Ti-6Al-4V part showed a changing thermal gradient along the build height during material deposition. Where a martensitic microstructure developed in the first layers which had a higher thermal gradient, however a α-β Widmanstätten structure was formed in later layers as the deposition progressed and the thermal gradient reduced [10].

- DED-arc of alloy 625 has shown tensile strength to decrease with sample height. This was attributed to a deleterious phase called Laves, which precipitated more readily in upper layers due to heat accumulation [11] .

- Ti-6Al-4V samples with different geometries were designed to have comparatively different heat loss through conduction over time. As a result, different microstructures developed. Smaller conductive areas resulted in a α+β lamellar microstructure instead of being fully martensitic, see Figure 3 [12].

- Through in-situ melt pool monitoring during a DED process of Ti-6Al-4V, thermal gradients showed a decrease of 8000 K/cm in the 1st deposited layer, to 3700 K/cm in layer number 148 [13].

Strategies of removing texture and promoting equiaxed grain growth involves changing processing parameters so that G/R < 1. Post fabrication heat treatment may reduce texture to some extent as well, particularly if phase transformations are involved. There is a risk associated with using AM-components without a clear understanding of how the processing parameters influence microstructural evolution and anisotropy. Today this is an active and ongoing area of research.

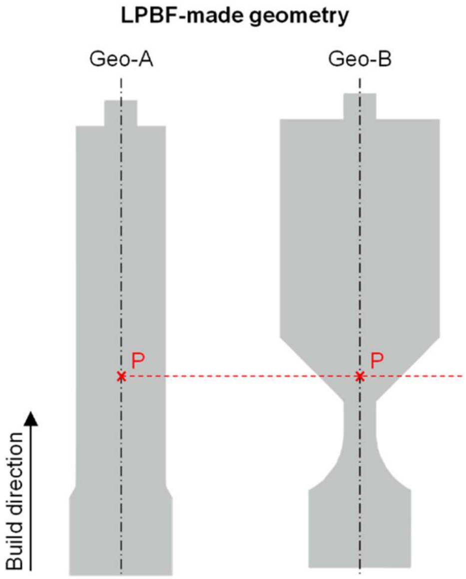

Figure 3: Points evaluated in two PBF produced samples "Geo-A" and "Geo-B", the latter showed less martensite evolution due to restricted heat conduction [12]

6.2 As-built vs. post build heat treatment

Due to rapid solidification and repeated reheating, the microstructures formed during AM will often contain considerable thermal stresses and can also be inhomogeneous. Post-AM heat treatment is often used to mitigate these residual stresses and inhomogeneities. Typically, improving toughness at the cost of reduced strength. For materials that undergo phase transformations after solidification, the heat treatments will also homogenise the microstructure. Depending on material and desired properties solution treatment and aging may be utilised.

Furthermore, thermomechanical hot isostatic pressing (HIP) is another method that can be used to both eliminate porosity and change the microstructure of AM parts. HIP'ing can have a beneficial effect on ductility and fatigue resistance especially for samples with polished/machined surfaces containing porosity type defects.

6.3 Microstructure and properties of AM-produced austenitic and martensitic stainless steels

The stainless steels are a broad group of alloys that that offer better corrosion resistance than other iron-based alloys. A minimum of 12wt.% Cr is generally needed to classify a steel as stainless due to the creation of a passive oxide film (typically Cr_2O_3) that is a few nm thick. Further additions of Ni, N and Mo may aid this passive film in upholding its integrity against localized attacks such as pitting corrosion. Stainless steels are currently the third-most preferred material for AM, with grades such as 316L and 17-4PH seeing most use. By 2027 stainless steels are expected to account for most of the AM market share at 33% [14].

Whether a stainless steel is comprised of ferrite, austenite, martensite or a combination of these phases, is decided by heat treatments and the composition of alloying elements. The austenitic stainless steels are austenitic due to additions of Ni and Mn that open the γ-field in the Fe-C phase diagram, suppressing ferritic transformation. With moderate tensile strengths of 500-600MPa, elongations of up to 50% and great corrosion resistance, the austenitic steels are widely used offshore. Conversely, wrought 17-4PH is classified as a martensitic stainless steel but see inherent challenges with regards to AM as the as-built microstructure consists of a large fraction of retained austenite. This section describes the properties and challenges of these steels when produced through AM.

6.3.1 Properties and microstructure of 316L

The austenitic alloy 316L was used in some of the earliest demonstrations of PBF. At this stage, in the early 2000s, the balling effect as described in Section 7.4 was a substantial problem and a relative density in parts of 99.9% was unattainable. Finally, in 2010 a relative density of 99.9% was achieved [15]. Microstructures in PBF-LB produced austenitic stainless steels such as 316L have been reported to be fully austenitic with a very fine columnar solidification structure compromised of cells smaller than 1 µm. Many such cells sharing the same crystallographic orientation form one grain, which is typically finer than those observed through traditional manufacturing [16], [17]. Depending on the manufacturing process, different microstructures are observed for 316L. According to the Schaeffler diagram this alloy may also consist of a ferritic phase upon solidification. Scanning electron microscopy (SEM) on a DED sample confirms this notion as microsegregation of ferrite stabilizing elements cause fine ferritic films to form on the solidification cells, Figure 4 [18], [19].

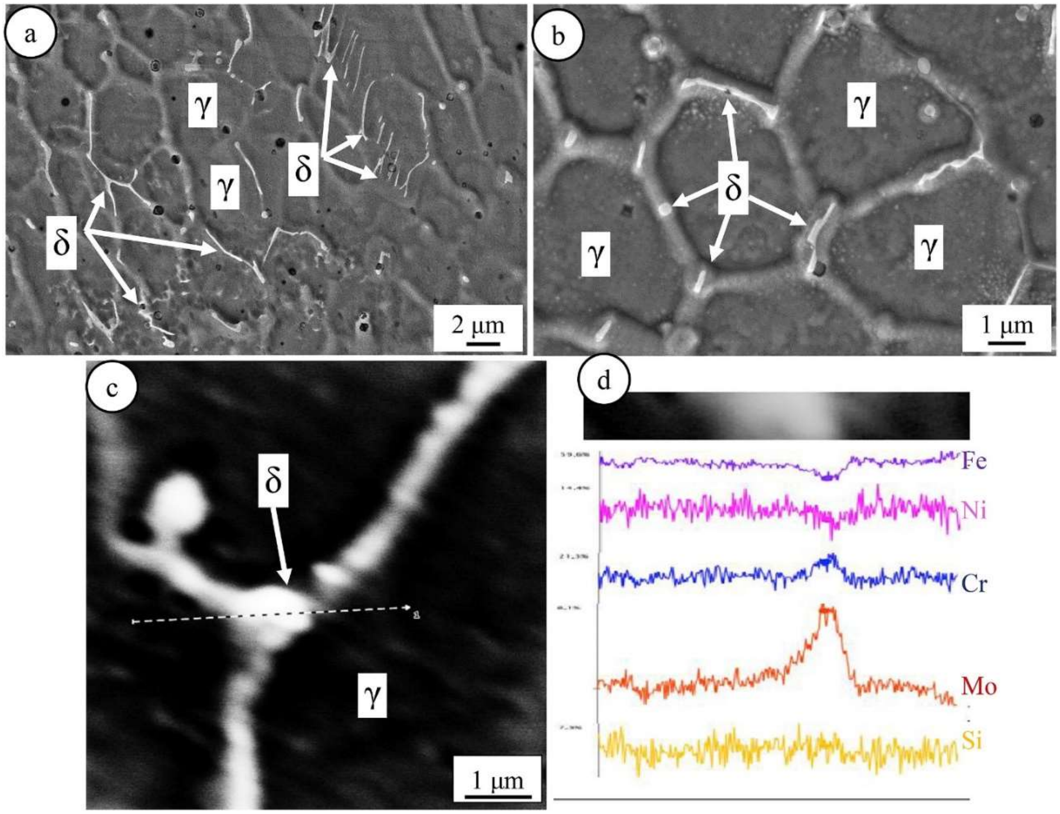

Figure 4: Image showing a-b) SEM images of proposed phases; c-d) EDS (Energy dispersive spectroscopy) line scan confirming constituents to be ferrite formers [20]

Only a handful of studies report on remnants of δ-ferrite in the as-built state of PBF manufactured 316L [21], [22]. Generally, the most common microstructure is reported to be fully austenitic [23], [16].

The fine columnar solidification structure of as-built 316L and higher dislocation density due to thermal stresses, produces higher ultimate tensile and yield strength than that of conventionally manufactured parts. While some works have found elongation of failure (EoF) as low as 12% (partly attributed to sufficient powder melting) [24], [21], many studies report higher EoF, up to 67% [25], [26], [27]. Note that the high variability is caused by the integrity of the setup and processing parameters used during printing. Alloy 316L in its as-built condition possesses great tensile properties that are not significantly altered by heat treatment. With annealing up to 800 C° microstructure remains the same while providing stress relief. Above this temperature recrystallization occurs and above 1150 C° partial transformation to δ-ferrite occurs as predicted by equilibrium phase diagrams.
High surface roughness of 316L is particularly detrimental to fatigue properties. It has been observed that the fatigue limit can be increased by a factor of two when surface finishing is applied to printed parts, which allows for competition with conventionally wrought parts. Stress relief, HIP and annealing have only shown slight improvements in fatigue properties [16].

With respect to corrosion, PBF-LB produced 316L can achieve a higher resistance than wrought material [28], [29]. While the resistance to pit initiation is higher, the ability to repassivate ("arrest" the pit) once a pit has initiated is lower. Higher corrosion resistance is attributed to fewer/smaller MnS inclusions that cause Cr-depleted zones and act as nucleation sites for pitting [30]. Smaller and fewer MnS inclusions are thought to be the result of high cooling rates.

6.3.2 Properties and microstructure of 6Mo

The use of stainless steels in seawater and other aggressive environments is mainly limited by their susceptibility to localized forms of corrosion such as pitting. Comparisons of different grades of stainless steels can be made by comparing the pitting resistance equivalent number (PREN). Alloy 6Mo has a PREN higher than 40, making it well-suited for applications in seawater. No papers have been found on the properties of 6Mo produced through AM. Laser cladding has shown promising results with less than 1% of the microstructure consisting of detrimental secondary phases, namely Chi, Laves and σ in interdendritic regions. Dendrite cores had PREN values higher than 40 and the corrosion resistance did not deviate from what is common in parts produced by traditional manufacturing [31].

6.3.3 Properties and microstructure of 17-4PH

In its wrought form, the solidified microstructure of 17-4PH can be fully martensitic and is promptly subjected to further processes of aging and strengthening by formation of Cu-rich precipitates. Note that the martensitic finish temperature (Mf) exists at around 32 °C, so small deviations in processing may yield differing amounts of martensite in the solidified microstructure. Most literature has been devoted to parts produced by PBF, which is the only manufacturing method discussed here.

Current efforts in AM of 17-4PH, aim at reproducing the fully martensitic microstructure observed in conventionally produced components. This is challenging in the case of PBF, due to the amount of retained austenite that exists in the as-built condition. The microstructure is commonly dominated by austenite, with one article finding 72% austenite and 28% martensite [32]. Furthermore, variations exist in microstructure due to inherent issues with reproducibility, which causes a large spread in tensile properties. This has led to increasing efforts in identifying heat-treatment procedures that can produce fully martensitic microstructures, remove texture and contribute to appreciable precipitation strengthening. Through implementation of the recommended homogenization heat treatment of aerospace materials ASM 5355, dendritic structures have been eliminated and resulting microstructure was compromised of 10% austenite with 90% martensite [33]. Other studies have shown that the heat-treated state of 17-4PH produces microstructure similar to that of wrought materials [34], [35]. The tensile properties can achieve values that are as good or even surpasses conventionally produced parts given that proper heat treatment to produce a fully martensitic microstructure is employed [36], [37].

Granted that a part has achieved full density, the corrosion resistance of AM-produced 17-4PH is better than for conventional parts [38] [39]. This is attributed to phenomena as stated below:

- PBF produces refined lath martensite and fine homogenously distributed NbC precipitates.
- Increased stability of the passive film due to a higher nitrogen content stemming from N_2 gas atomization.

6.4 Microstructure and properties of AM-produced duplex stainless steel

Duplex stainless steels (DSSs) obtain their properties from having a high content of elements which provide corrosion resistance in marine environments combined with a two-phase microstructure where ferrite provides strength and austenite provides ductility. A phase distribution of approximately equal amounts of austenite and ferrite is usually considered to provide the best combination of properties [40]. DSSs have been used successfully with AM [41], [42], [43], [44], [45], and the phase transformation from ferrite to austenite helps avoid hot cracking which can typically be challenging with austenitic stainless steels. However, the alloying elements that provide duplex alloys with their desirable properties can also lead to precipitation of detrimental microstructural constituents during AM of DSSs.

The different AM techniques produce a range of cooling rates, however they also allow for reheating during the manufacturing process, which is important for the microstructure creation in duplex materials. The primary solidification mode for duplex steels is ferritic, and with the high cooling rates encountered during AM, the initially solidified microstructure will be almost purely ferritic for conventional feedstock compositions, both with PBF and DED. This microstructure will typically contain coarse columnar ferrite grains with narrow bands of grain boundary allotriomorph austenite precipitated along the ferrite grain boundaries. Inside the ferrite grains, the supersaturation of nitrogen will lead to heavy precipitation of chromium nitrides. This microstructure is illustrated by the upper half of Figure 5. During deposition of subsequent layers with DED techniques, the reheating from the layer above will lead to further austenitic grain growth, but an inhomogeneous microstructure will typically be the result, as shown in the lower half of Figure 5.

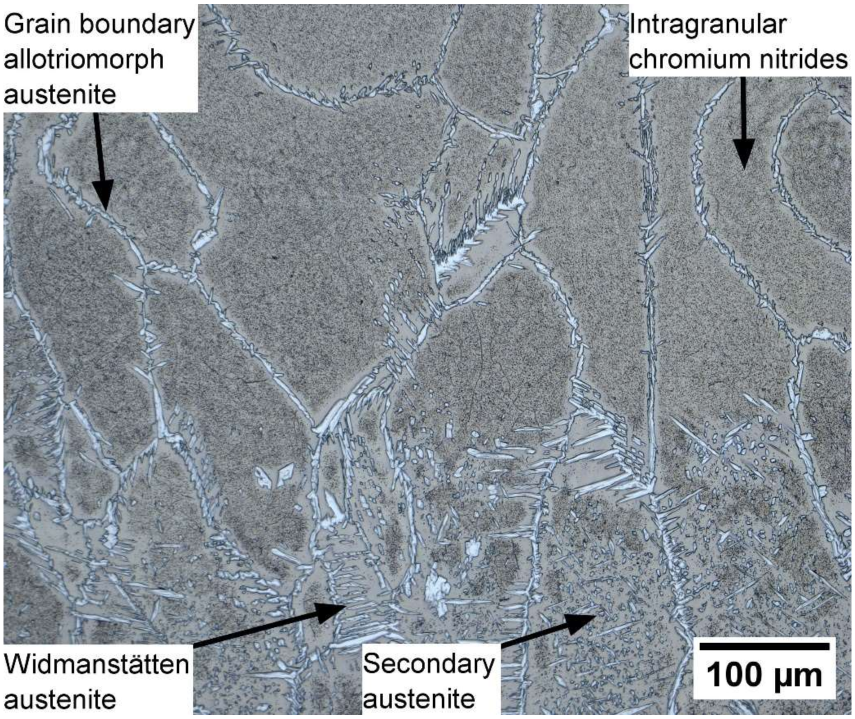

Figure 5: Typical DED-LB as-built microstructure of 2205 duplex [46].

Solution annealing will quickly reset the microstructure, and the equilibrium phase balance will typically be established within 15 minutes at solution annealing temperature. This increases impact toughness considerably, while the strength will be slightly reduced for DED material and considerably reduced for PBF material.

The PBF-LB process produces high cooling rates, and limited reheating, which results in almost purely ferritic as-built microstructures. EOS is one of the manufacturers that have countered this by supplying feedstock powder with elevated nickel content, which, according to EOS, produces an acceptable phase balance in the as-built condition, but an excessive amount of austenite if solution annealed. EOS have not published corrosion test results for this feedstock.

Both DED-Arc and DED-LB may cause excessive heating of the part if heat management is not considered during process parameter development. This has been shown to cause sigma phase precipitation in as-built 25Cr material [44], [46]. To counter this, an idle time is typically introduced to allow cooling between passes.

Feedstock composition is a very important topic for DSSs, since the composition is one of the main deciding factors for the microstructural development. With DED-Arc and DED-LB/wire, the use of welding consumable as feedstock has been a common practice. The elevated nickel content in 2209 and 2509 welding wires may result in reduced corrosion resistance as well as in insufficient strength of the deposited material [47]. It may be favourable to apply a feedstock with elevated nickel and nitrogen content if the material is to be used in the as-built condition, but if the same material is solution annealed, the austenite fraction will typically be excessive leading to reduced strength and lower corrosion resistance than what can be achieved with conventional compositions like 2205 and 2507. Currently, there are no 2507 feedstock wires commercially available, making 25Cr duplex a challenge for wire-based techniques.

6.5 Microstructure and material properties of AM-produced titanium parts

Upon rapid cooling in alloys containing β-stabilizing elements, transformation to the α phase is delayed due to slow diffusion, leaving it supersaturated in the β-stabilizing elements. This makes the transformation a displacive martensitic transformation (diffusionless nucleation and growth), with the resulting phase being called α’. Regardless of manufacturing technique, Ti-Al6-4V is usually annealed to remove martensite from the final product as it is detrimental to corrosion resistance and the desired mechanical properties. Complications arise with regards to AM as the high cooling rate and complex reheatment cycles, create a substantial amount of martensite with differing morphologies. Therefore, the manufactured component needs to undergo appropriate heat treatment.

6.5.1 Microstructure

Depending on the AM-process, the resulting microstructure of an as-built Ti-6Al-V sample may be compromised of differing martensite phase fractions. In DED and PBF, martensite is thought to be the dominant phase [48]. Furthermore, the martensite formed through AM processes, possess different characteristics and morphologies to that of traditionally manufactured parts. From largest to smallest, subclassifications of primary, secondary, tertiary and quartic martensite will form due to different thermal cycles and increasing ambient temperatures[49]. See Figure 6 for a light optical microscopy (LOM) image of the different martensitic types. The microstructural evolution of martensite in as-built AM fabricated titanium components is complex and still an area of research.

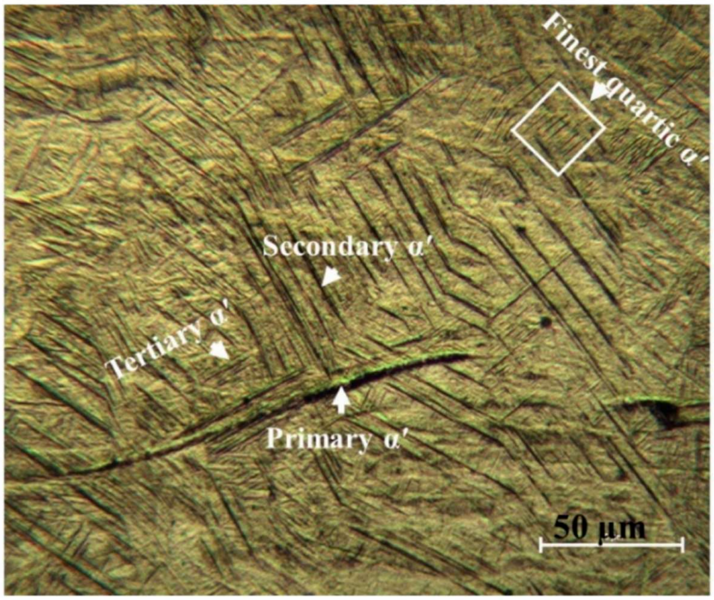

Figure 6: LOM image of PBF-produced Ti-6Al-4V [50]

6.5.2 Mechanical properties

In the as-built state, additively manufactured Ti-6Al-4V alloys are unable to achieve the desired mechanical properties of their wrought competitors. While martensite increases the ultimate tensile strength of up to 1200MPa, ductility and toughness remains low, with incidents of EoF being less than 5% [51].

The microstructural evolution of martensite is undesired due to the properties mentioned above, heat treatment through HIP and annealing have shown to produce great mechanical properties that could compete with conventionally manufactured components. HIP is generally used to close pores and remove dislocations, while the primary objective of annealing is to decompose martensite into α and β phases. *Haar et al. [6]* annealed PBF produced Ti-6Al-4V in different solid solution temperature regions (SSTR). Depending on the heat treatment process, markedly different ductility was achieved.

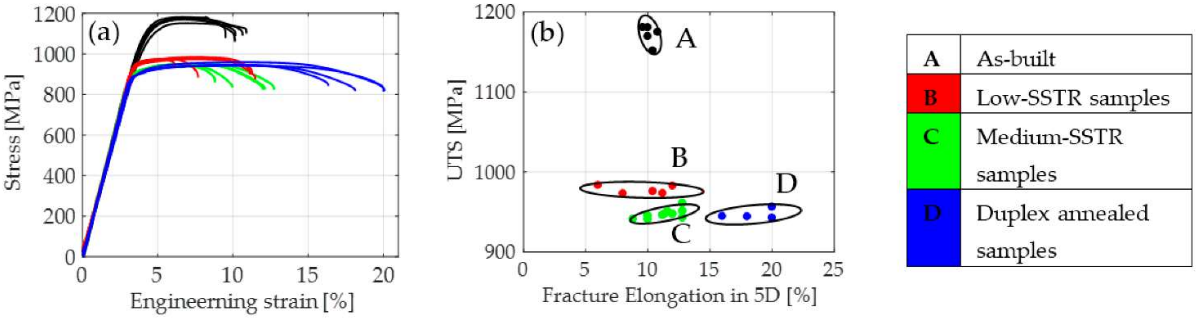

Figure 1: Plots of a) tensile stress curves and b) ultimate tensile strengths, for four groups of samples each treated in different SSTR-regions [52].

As can be seen in Figure 1, ductility improves through duplex annealing and coincides well with the ductility one would expect from wrought and annealed Ti-6Al-4V. It is important however to note that microstructure in the duplex-annealed state was composed of 41% primary and secondary martensite. The high fraction of martensite is a biproduct of quenching from the annealed state rather than continuous cooling. Quenching was deemed necessary to maintain a strength that can compete with traditionally manufactured Ti-6Al-4V. While the mechanical properties are great, its corrosion resistance may suffer in this regard and therefore poses a great risk for use offshore.

6.5.3 Corrosion resistance

The corrosion resistance of as-built AM Ti-6Al-4V has been shown to be up to sixteen times worse than wrought samples in an aqueous solution containing 3.5wt.% NaCl [53]. Through annealing at 800C° for two hours, corrosion rates were decreased to that of wrought Ti-6Al-4V. Compared to the heat treatment proposed by Haar *et al*. in section 6.5.2, the alloy was continuously cooled in a furnace environment, thereby restricting the formation of martensite.

Based on the literature search in this section, it seems that good corrosion resistance comes at the cost of tensile strength in AM of Grade 5 titanium alloys due to formation of martensitic phases [54], [55]. The consensus, however, is that more research needs to be devoted to the topic of corrosion. Given that the alloy undergoes suitable heat-treatment, there are no significant risks associated with using the alloys for offshore applications provided that the mechanical properties are known, and that no martensite remains. In practice such a result may be challenging to achieve.

6.5.4 CP titanium

Comparatively to Ti-6Al-4V, chemically pure(CP) titanium has been researched far less with regards to AM. Thermodynamically however, these alloys are prone to form the same acicular martensite that is common in α-β titanium alloys. The mechanical properties of AM-produced CP titanium are oftentimes better than for cast material, with a higher UTS (ultimate tensile strength) and EoF even in the as-built state, but a tendency of anisotropic behaviour [56], [57]. Traditionally manufactured CP titanium sees use offshore primarily due to its corrosion resistance. A risk associated with using this material offshore would be that almost no research has been conducted to assess the corrosive properties of this alloy in connection to AM. Here the martensitic phase may cause complications if not fully removed through annealing.

6.6 Microstructure and material properties of AM-produced nickel-based superalloys

Unlike in titanium and some stainless steels, the nickel-based superalloys are not predisposed to the same martensitic phase transformations upon rapid cooling.

6.6.1 Microstructure

The as-built microstructure of a nickel-based superalloy is comprised of an austenitic face centred cubic matrix called gamma (γ). In addition, a variety of secondary precipitates may form depending on the alloying composition. Additions of 0.05-0.20wt.% carbon cause precipitation of carbides such as MC, $M_{23}C_6$, M_6C and M_7C_3. Literature remains relatively undecided on the exact contribution that carbides have on mechanical properties. While they reduce cracking propensity by diminishing the content of low-melting point eutectic phases in cast alloys, they could inadvertently increase cracking propensity in samples produced by AM [9,10]. The high cooling rates induced by AM causes a higher density of carbides to precipitate, but with a finer more spherical morphology. The carbides form extensively within interdendritic regions, which may be a major mechanism in solidification cracking as they obstruct the shrinking of residual liquid in the later stages of solidification [58].

In addition to the main austenitic γ-phase and carbides, the formation of an intermetallic precipitates γ' ($Ni_3(Ti, Al)$) and γ'' (Ni_3Ti/Ni_3Nb) provides strengthening, while topologically close packed phases such as δ, µ and Laves are detrimental if detected above trace amounts [8].

Empirically, the success in which Ni-based superalloys have seen with regards to AM in their as-built state, is highly linked to the content of Al and Ti. The higher this content, the more difficult they are to print due to an increased propensity to hot cracking.

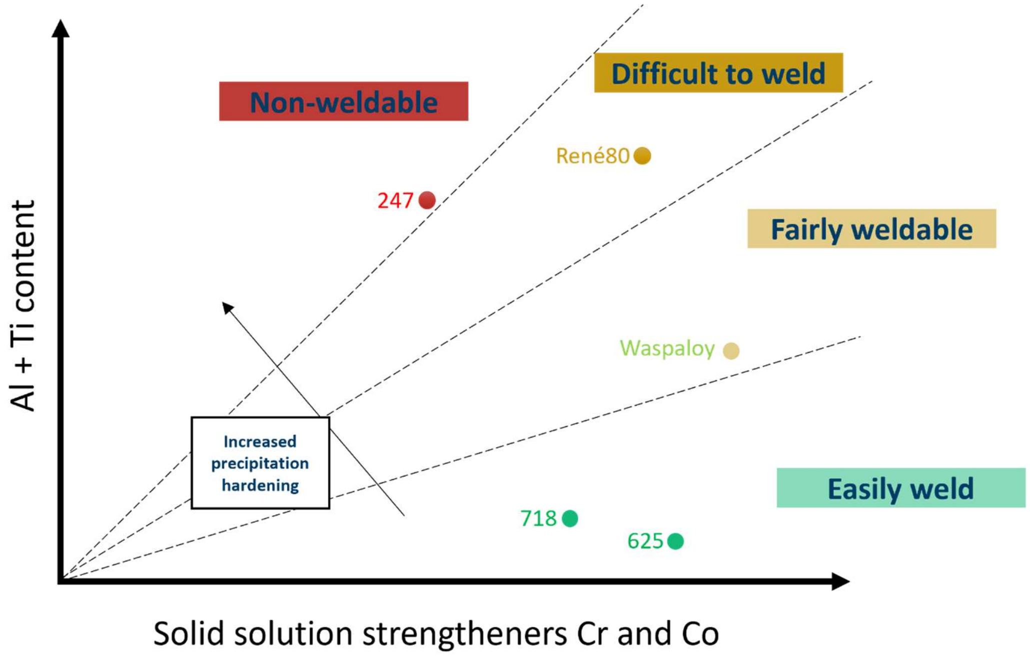

Figure 7: Weldability diagram for a collection of Ni-based superalloys. Empirically translates to their printability

As can be seen from Figure 7, both alloys 718 and 625 are well-suited for AM applications.

6.6.2 Mechanical properties

Balachandramurthi et al [59] investigated the effect of post processing through HIP, solution treatment and ageing (STA) on mechanical properties of alloy 718 produced through PBF-EB. Their findings are summarized below in Table 1. It is apparent that alloy 718 in its as-built state possesses good mechanical properties, and that post-processing further enhances these.

Table 1: Tensile properties of PBF-EB manufactured alloy 718 [59]

Material condition	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Young's Modulus (GPa)
As-built	920 ± 16	1075 ± 46	10 ± 3	138 ± 5
STA	1096 ± 6	1172 ± 30	6 ± 1	137 ± 7
HIP + STA	1100 ± 13	1190 ± 33	14 ± 1	142 ± 4
Cast (AMS 5383)	≥ 760	≥ 860	≥ 5	-
Wrought (AMS 5662)	≥ 1034	≥ 1275	≥ 12	-

6.6.3 Corrosion resistance

Experiments have shown better corrosion resistance in the additively manufactured as-built state of alloy 625 compared to conventionally produced parts [60]. A comparative study of the triboccorosional properties of alloy 718 have also been done, which showed a higher resistance to synergistic corrosion and wear for PBF-produced 718 as compared to a cast product in 3.5wt.% NaCl aqueous solution [61]. Another article shows inferior properties when comparing 718 produced by DED-arc to that of a wrought one. A passivation current density of 421 ± 57 was found in the AM produced alloy, with 27 ± 4.9 $\mu A/cm^2$ in the wrought one [62]. Significant improvement in PBF-printed alloy 718 has been achieved through solution treatment at 1020 C°**,** due to elimination of microsegregation. The onset of corrosion in AM fabricated Ni-based alloys is currently attributed to microgalvanic coupling between the austenitic γ-phase and secondary precipitates, which is suppressed through heat treatment [63].

7 Metallurgical failure modes in AM produced components

The different manufacturing methods and alloys are susceptible to different failure modes. The reported mechanical properties of metal AM materials vary significantly between studies, especially showing large scatter in fatigue tests. The upcoming ‘ISO/ASTM CD 52954-1 Additive manufacturing — Qualification principles, Part 1: Common failure modes used for risk mapping’ will identify common failure modes which typically occur within AM process categories and aims to close the existing gap between general risk management standards. The document can be used to aid manufacturers in their risk management. Release date for ISO/ASTM CD 52954-1 is currently unknown.

While microstructure is important, and its formation mechanisms and effect on mechanical properties is well described, the formation and effect of defects is less clear. Where in PBF both the powder (size distributions, quality and moisture content) and process parameters (power, scanning strategy, speed, layer thickness and hatch spacing) heavily influence the microstructure and defect formation in the resulting material. This is important as in particular the fatigue performance of AM metals is significantly influenced by the existence of defects such as gas porosities and lack of fusions (LOF), where characteristics such as size, shape, location, density, and distribution have shown to play key roles in the fatigue performance of AM metals. Meaning considerable effort to mitigate the formations of unwanted microstructures and defects is typically done through process optimisation and postprocessing.

7.1 Pores

The term pore simply refers to any defect that occurs due to the absence of material, thereby inducing porosity. To understand how defects impact mechanical properties, it is helpful to examine cast metals where it is well established that porosities lead to poor mechanical properties. During the casting process, trapped gas forms large pores, sometimes several millimetres in diameter. However, there are techniques to reduce the size and extent of this porosity. Specifically, casting simulation methods can optimize injection velocity, the placement and design of casting ingates, and cooling zones on the mold [64]. Gas pores also occur during AM either due to gas trapped in the raw metal powder particles or trapped inert environmental gas during the melting process. Gas pores are typically characterized by spherical morphology. Porosity induced by trapped gas is more difficult to eliminate than LOF in AM parts. Mechanisms of gas pore formation during a DED process is shown in Figure 8.

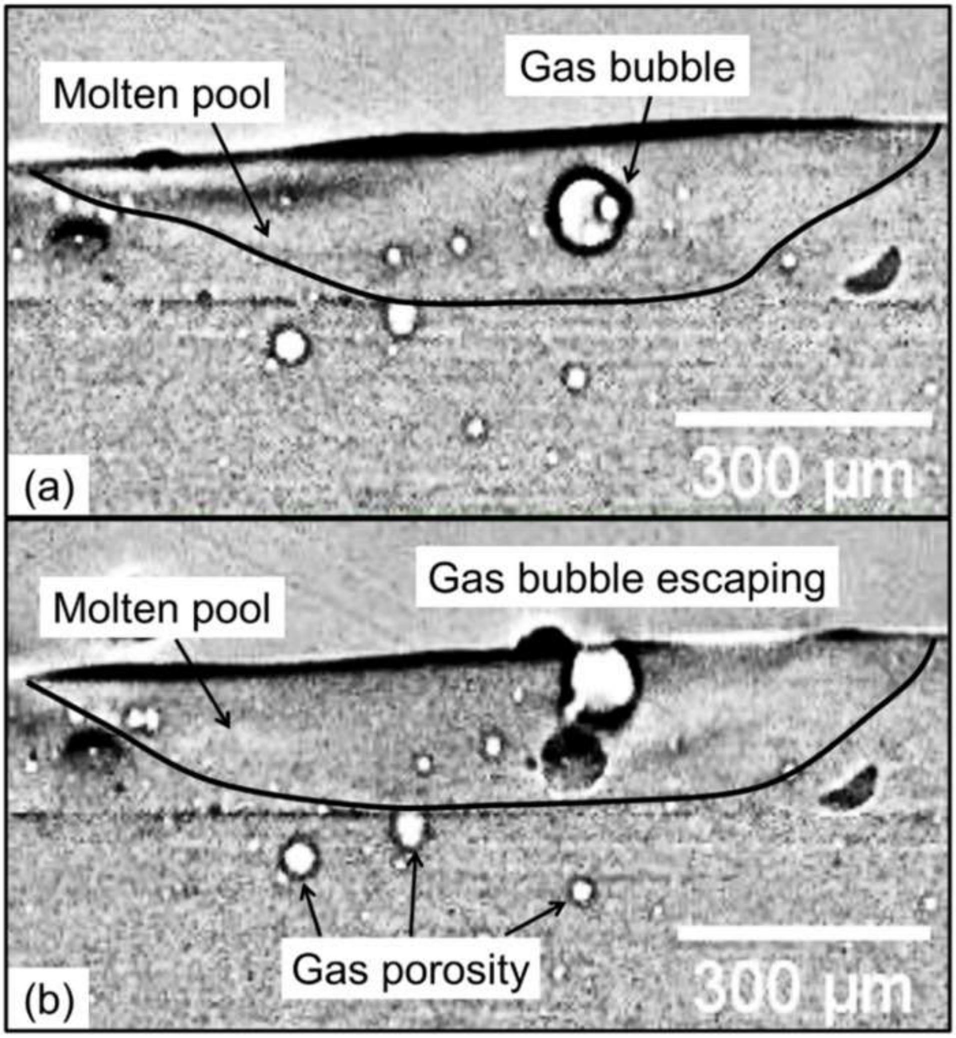

Figure 8: Formation of pores/voids due to mechanisms of gas porosity [65]

7.2 Lack of fusion

Non-sintered area or delamination, improper fusion between successive tracks or layers causes what is known as LOF. This phenomenon is also encountered during improper welding. Higher energy supply and lower hatch spacing have shown to decrease LOF defects, which commonly take on the shape of large irregular pores [66], see Figure 11. A proper control, repeatability and understanding of processing parameters is essential in limiting the risks associated with LOF.

7.3 Keyholing

The term “vapour depression” may be applied to any shape of cavity caused by recoil pressure during vaporization of a liquid surface [67]. This is a broader and more inclusive term than a “keyhole”, which was adopted from the welding community in the early days of deep penetration laser and electron beam technologies [68]. Recent studies have aimed at categorizing the mechanisms behind keyhole pore formation, and three modes of keyholing have been identified through in-situ x-ray imaging [69]:

- Keyholes forming pores at the end of a metal track, due to the thermal heat source stopping or turning around
- The instant bubble by a ledge on the middle of the rear keyhole wall, disappearing through keyhole fluctuations
- The keyhole pores forming at the bottom of melt pools due to keyhole fluctuations

Of these, the last mechanism is most important, as pores at the end of a track can be eliminated through contour scanning and post process machining. Furthermore, the instantaneous bubbles disappearing through fluctuations do not form pores. See Figure 9 for a schematic on how pores form through keyhole fluctuations.

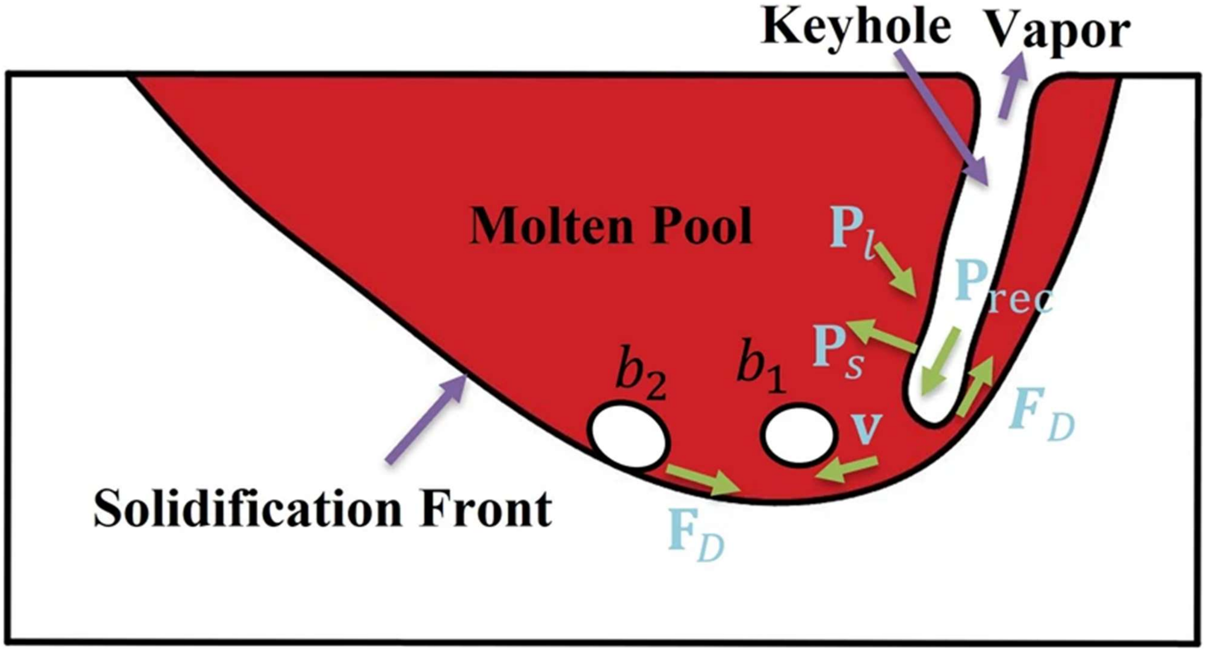

Figure 9: Schematic showing of how keyholing creates pores that are detrimental to material quality. P_{rec} is the recoil pressure by evaporation, P_l the hydrodynamic pressure, P_s surface tension and F_d drag force. The bubbles b1 and b2 do not float due to Bernoulli's principle and are caught by the solidification front to develop pores [69].

7.4 Balling defects

Balling refers to the breakup of continuous melt pools into melt agglomerates. When this mechanism is pronounced in PBF, it may produce a non-uniform powder distribution in consecutive powder layers, poor wettability of previous layers, pore formation and in extreme cases; interruption of the build process [70], [71]. All these factors contribute to surface roughness and porosity. Balling has been observed at high laser scan-speeds with a combination of both low and high laser power, as well as at low scan speeds with high laser power [72], [73], [74].

Balling, gas pores, LOF, and pores formed due to keyholing all lead to undesirable material properties. For PBF, while adjusting scanning speed and laser power to reduce one specific defect, it may cause the introduction of another. Therefore, process maps have been developed to define the parameters that aid in the production of fully dense parts, a simple illustration can be seen in Figure 10.

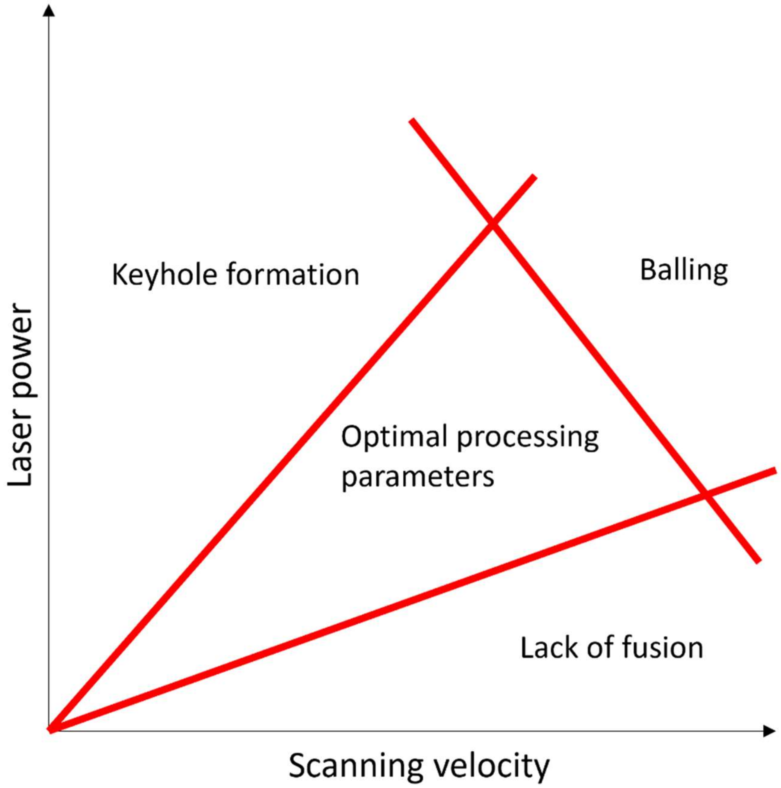

Figure 10: Illustration of a process map. Naturally these will vary between methods

7.5 Unwanted phase creation

Thermal history influence phase creation differently in different materials. Rapid increase and fall in temperature in the melt pool creates unique phases. With a basis in section 6, detrimental phases that are precipitated through AM are presented below in Table 2 and Table 3. The tables cover common unwanted microstructural components that exist in the as-built state.

Table 2: Detrimental phases that may form through PBF of different alloys

PBF		
Material	**Detrimental phases**	**Effects**
316L	δ-ferrite may form, generally microstructure tends to be fully austenitic	May increase susceptibility to pitting corrosion and is known to form σ upon thermal processing
Duplex	Chromium nitrides	Slightly reduced low-temperature impact toughness and slightly reduced corrosion resistance
6Mo	Lack of scientific literature	-

17-4 PH	Retained austenite and/or δ-ferrite, heat treatment necessary	Widely different properties from what is expected of 17-4PH unless heat treated
Ti-6Al-4V	Martensitic phases, some are distinct for AM. Likely needs heat treatment for use offshore.	• Reduced fatigue life • Increased Tensile strength • Lower ductility • Less corrosion resistant
CP Titanium	Far less researched than Ti-6Al-4V but prone to form similar martensitic phases. Likely needs heat treatment for use offshore	• Reduced fatigue life • Increased Tensile strength • Less corrosion resistant
Alloy 625	δ, μ and Laves, certain carbides	Generally, cause embrittlement and may affect corrosion resistance
Alloy 718	δ, μ and Laves, certain carbides	Generally, cause embrittlement and may affect corrosion resistance

Table 3: Detrimental phases that may form during DED of different alloys

DED		
Material	**Detrimental phases**	**Effects**
316L	More δ-ferrite forms than in the PBF process	May increase susceptibility to pitting corrosion and is known to form σ upon thermal processing
Duplex	Chromium nitrides, chi/sigma phase	Chromium nitrides: Slightly reduced low-temperature impact toughness and slightly reduced corrosion resistance Chi/sigma phase causes embrittlement: Considerably reduced low-temperature impact toughness and considerably reduced corrosion resistance, reduced fatigue life
6Mo	Lack of scientific literature, cladding produces Chi, Laves and σ within acceptable amounts	-
17-4 PH	Retained austenite and/or δ-ferrite,	Widely different properties from what is expected of 17-4PH unless heat treated

	heat treatment necessary	
Ti-6Al-4V	Martensitic phases, some are distinct for AM. Likely needs heat treatment with regards to use offshore.	• Reduced fatigue life • Increased Tensile strength • Lower ductility • Less corrosion resistant
CP Titanium	Less researched than Ti-6Al-4V but prone to form similar martensitic phases. Likely needs heat treatment for use offshore.	• Reduced fatigue life • Increased Tensile strength
Alloy 625	δ, μ and Laves	Generally, cause embrittlement and may affect corrosion resistance.
Alloy 718	δ, μ and Laves	Generally, cause embrittlement and may affect corrosion resistance.

7.6 Surface Roughness

One of the major benefits of AM is the freedom to design complex geometries. In designing these geometries however, the engineer must assess the ability to machine surfaces post-fabrication. This needs to be assessed because of surface roughness, which is one of the main driving forces of reduced fatigue performance. At or close to the surface failure may initiate from LOF, pores and/or crack initiation sites. In almost all as-built specimen failure will initiate in the surface. Further propagation will be dependent on microstructure [75], [76], [77]. Combating surface roughness is typically done through machining of the as-built part, which may be complicated by restrictive geometries. It is therefore critical for designers and engineers alike, to understand how surface roughness develops through AM and select appropriate designs for specific applications.

7.7 Typical defects and integrity challenges for DED parts

DED techniques have more in common with welding than PBF. Because of this, the failure modes have more in common with welding defects than PBF. As an example, density is generally not an issue with DED material, except for extreme cases of contamination leading to porosities. Scattered porosities can be observed in DED material, but not to the extent that they will influence the properties.

For the DED methods, the deposition paths can be very important and must be matched with the process parameters to avoid introduction of defects. If this is not well managed, systematic lack of fusion can be introduced during the deposition process.

On the other hand, thermal management is also important. This needs to be balanced so that sufficient heat is provided to avoid lack of fusion, but it also needs to be sufficiently low to avoid overheating, which will impact both process stability and microstructure development.

An important parameter for the deposition paths is the layer height or layer thickness. This parameter needs to be determined for the specific part, deposition path and process parameters. Figure 11 shows an example of how insufficient wire feed speed during deposition of the first 7 layers resulted in cumulative layer height deviation, which in the end caused lack of fusion throughout the interface between layer 7 and 8. The specimen shown in Figure 11 was deposited with coaxial-DED-L/wire, a process which is sensitive to layer height deviations. DED-Arc will in general be more robust against layer height deviations since the arc follows the wire stick-out, and some variation can be accommodated by the GMAW equipment.

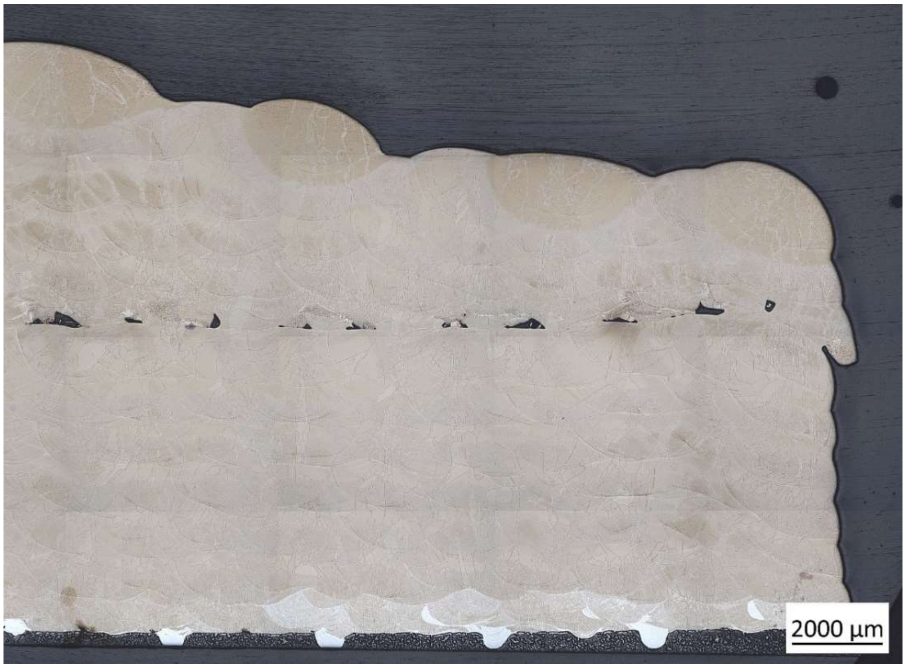

Figure 11: Lack of fusion caused by cumulative layer height deviations in a 2205 duplex part.

DED equipment can come in a wide range of types, from robot-mounted deposition heads to enclosed cabinet-type machines. Because of this wide range, the manufacturer of the system will not always be able to perform all calibration, which may lead to operator-induced variation, e.g. when setting substrate coordinate system. Enclosure-type machines can more easily be set up with probes to avoid this variation but will still require that this is included in the design of the machine.

When using DED with a manipulator that allows tilting and rotation of the substrate, it is possible to deposit material in different positions beyond perpendicular to build direction, allowing even sharp overhangs. With more possibilities on how to build a part the qualification of the build process parameters increases. With more build freedom comes more complexity in qualification and quality control.

7.8 Challenges with finding defects in AM builds

With new production facilities making use of a technology that require new methods for quality assurance the importance of manufacturing methods understands increase.

Computer tomography (CT) is commonly used for non-destructive testing of AM material. Since it is an X-ray based technique, it is excellent for detecting voids, a typical challenge with PBF material. However, for lack of fusion in DED material, it has been observed that industrial CT scanning failed to detect systematic lack of fusion, which opened up during subsequent tensile testing [78]. At the same time, the lack of fusion had such a limited extent that it did not influence the yield and tensile strength significantly, but this could have been more critical for fatigue properties.

8 Information from NCS operators

The validity in conducting statistical analysis and drawing conclusions from a survey, is in large defined by the sample-size of respondents. The primary objective in analysing quantitative data, is to ensure that this sample size represents the entire population accurately through statistical interference. Doing so is not feasible through the survey conducted in this report. While the survey may accurately represent the largest operators on the NCS as this population size is small, it may not capture the entirety of Norwegian oil and gas sector. Questions were fronted to give a qualitive indication of the usage, knowledge, production and outlooks that four major operators foresee through implementation of AM on the NCS. Each operator appointed one person to answer the survey.

8.1 Risks in context of the survey

- Sampling Bias: If the sample isn't representative of the population, the results won't be reliable. This can happen if certain groups are overrepresented or underrepresented.
- Response Bias: This occurs when respondents don't answer questions truthfully or accurately. This can be due to social desirability, misunderstanding the question, or simply not paying attention.
- Questionnaire Design: Poorly designed questions can lead to unreliable data. Leading questions, ambiguous wording, or complex language can confuse respondents and skew results.
- Non-Response Bias: If a significant portion of your sample doesn't respond, the results may not be reliable. Non-respondents might differ in important ways from those who do respond.
- Data Collection Method: The mode of survey administration (online, face-to-face, phone) can affect reliability. Each method has its own set of challenges and potential biases.
- Timing of the Survey: External factors at the time of the survey (e.g., current events, seasonal effects) can influence responses and affect reliability.

In this survey this can generate the following challenges:

- When answers are to reflect the view of AM for a company several respondents from each company would provide a better understanding of the status.
- One can argue that some of the questions are leading the respondents
- Respondent answers are not representative for the company but for the individual
- Some questions were not answered by all and we do not know why.
- Respondent answers what they want to answer and not what is the situation
- The risk of lack of understanding of AM to be able to put a number on the knowledge of others.

This survey is not meant to give an exact answer but a viewpoint of the situation and that is how this survey should be used!

The survey was conducted in Norwegian and questions that were asked are reiterated below in Norwegian. *Italic text* highlights a summary SINTEF Manufacturing has made based on the received answers.

8.2 Spørreundersøkelse med summerte svar

Omfang og motivasjon:

1. **Hvor mange AM-produserte metallkomponenter har dere bestilt totalt?**

Stor variasjon mellom operatører. Fra null til ca. 5000 deler der noen av delene har blitt produsert i utviklingsløp sammen med andre bedrifter.

2. **Hvor mange AM-produserte metallkomponenter forventer dere å ta i bruk i 2025?**

Fra 0 til ca. 1000 deler. En bruker skiller ikke mellom AM og andre metoder da operatøren stiller samme krav til materialegenskaper.

3. **Hvor mange AM-produserte metallkomponenter forventer dere å ta i bruk frem til 2030?**

Stor variasjon mellom operatørene. Samtlige forespeiler en betraktelig økning av AM deler, men dette avhenger av leverandørkjeden. Opptil 10 000 er en mulighet.

4. **Hvorfor ønsker bedriften din å ta i bruk AM som produksjonsmetode:**
   1)Designoptimalisering (bedre ytelse enn andre metoder)
   2) Ledetid (kortere enn andre metoder)
   3)Komponentkostnad (lavere kostnad enn andre metoder)
   4)Miljøhensyn

Ledetid er desidert den viktigste parameteren når det kommer til interesse for AM deler, med kostnader og miljø på andre plass. Nye designmuligheter nevnes som en måte å få bedre ytelse.

Kunnskapsgrunnlag:

5. **Hvilken usikkerhet ser dere med bruk av AM for et produkt som ble designet for en annen produksjonsmetode (f.eks. materialvalg, geometri og standarder)? Vil f.eks. tilvirkningsmetoden kunne påvirke egenskapene til produktet? Hva er dere sikre på, og hva er dere usikre på?**

Alle operatører har en bevissthet om at AM gir andre egenskaper enn tradisjonelle metoder. Variasjon i korrosjonsegenskaper ses som en større risiko enn styrken til metaller. Ansvar for materialegenskaper legges på leverandøren med en forventning om at de tar med seg kunnskap fra andre industrier og utfører kvalitetskontroll. Muligheten for å bruke AM på komponenter som er designet for tradisjonelle metoder er ikke alltid hensiktsmessig.

6. **Hvilken usikkerhet ser dere med bruk av AM for et nytt produkt som blir designet for AM? Hva er dere sikre på, og hva er dere usikre på?**

Operatørene forventer lav usikkerhet med sterk tro på AM. Mindre usikkerhet koblet til materialstyrke, men fremdeles usikkerhet koblet til korrosjon. Bruken av AM skaper et behov for designendring med tilhørende designverifikasjon, med potensielt krav til å kvalifisere en ny leverandør.

7. **Hvordan vil du vurdere kunnskapsnivået i din bedrift for de ulike delene av AM-prosessen, spesielt med hensyn til design og materialvalg?**
   Angi et tall for hvert alternativ (Skala 1-5, 1=veldig lavt 5= veldig høyt):

Gjennomsnittlig: 4,0; Høyest: 5; Lavest: 2

8. **Hvordan vil du vurdere kunnskapsnivået i din bedrift for de ulike delene av AM-prosessen, spesielt med hensyn til fremstillingsprosessen?**
   Angi et tall for hvert alternativ (Skala 1-5, 1=veldig lavt 5= veldig høyt):

Gjennomsnittlig: 4,0; Høyest: 5; Lavest: 3

9. **Hvordan vil du vurdere kunnskapsnivået i din bedrift for de ulike delene av AM-prosessen, spesielt med hensyn til varmebehandling og dens effekt på materialegenskaper?**
   Angi et tall for hvert alternativ (Skala 1-5, 1=veldig lavt 5= veldig høyt):

Gjennomsnittlig: 4,0; Høyest: 5; Lavest: 2

10. **Hvordan vil du vurdere kunnskapsnivået i din bedrift for de ulike delene av AM-prosessen, spesielt med hensyn til testing av AM-komponenter (destruktiv testing, NDT, FAT, etc.)?**
    Angi et tall for hvert alternativ (Skala 1-5, 1=veldig lavt 5= veldig høyt):

Gjennomsnittlig: 4,25; Høyest: 5; Lavest: 3

11. **Hvordan vil du vurdere kunnskapsnivået i din bedrift for de ulike delene av AM-prosessen, spesielt med hensyn til komponenter i praktisk bruk?**
    Angi et tall for hvert alternativ (Skala 1-5, 1=veldig lavt 5= veldig høyt):

Gjennomsnittlig: 3,75; Høyest: 5; Lavest: 2

12. **Hvordan vil du vurdere kunnskapsnivået i din AM-leverandørindustrien for de ulike delene av AM-prosessen, spesielt med hensyn til design og materialvalg?**
    Angi et tall for hvert alternativ (Skala 1-5, 1=veldig lavt 5= veldig høyt):

Gjennomsnittlig: 3,50; Høyest: 5; Lavest: 2

13. **Hvordan vil du vurdere kompetansenivået i AM-leverandørindustrien med hensyn til fremstillingsprosessen?**
    Angi et tall for hvert alternativ (Skala 1-5, 1=veldig lavt 5= veldig høyt):

Gjennomsnittlig: 3,75; Høyest: 4; Lavest: 3

14. **Hvordan vil du vurdere kompetansenivået i AM-leverandørindustrien med hensyn til varmebehandling og effekt av dette på materialegenskaper?**
    Angi et tall for hvert alternativ (Skala 1-5, 1=veldig lavt 5= veldig høyt):

Gjennomsnittlig: 3,75; Høyest: 5; Lavest: 3

15. **Hvordan vil du vurdere kompetansenivået i AM-leverandørindustrien med hensyn til testing av AM komponenter (destruktiv, NDT, FAT etc.)?**
    Angi et tall for hvert alternativ (Skala 1-5, 1=veldig lavt 5= veldig høyt):

Gjennomsnittlig: 3,75; Høyest: 5; Lavest: 3

16. **Hvordan vil du vurdere kompetansenivået i AM-leverandørindustrien?**
    Angi et tall for hvert alternativ (Skala 1-5, 1=veldig lavt 5= veldig høyt):

Gjennomsnittlig: 3,25; Høyest: 5; Lavest: 2

Bruk av AM:

17. **Når vil AM-deler tas i bruk?**
    1)Erstatningskomponenter /reservedeler
    2)Nyproduksjon av deler
    3) Begge

Alle svarer at begge er grunnen

18. Hvem/hvor i operatørens organisasjon vil beslutte om en komponent skal produseres additivt?"

Alle svarer at det blir et samarbeid mellom tekniske støttegrupper og utstyrsansvarlig.

19. Hvilke AM-metoder vil bli benyttet?

De aktuelle metodene er L-PBF og DED (primært DED-Arc) for respondentene.

20. Hvilke legeringer vil produseres additivt?

Definisjon: Legering er et metallisk materiale som består av minst ett metallisk grunnstoff og ett eller flere legeringselementer som ofte er metaller.

Titan, Duplex og Super Duplex, SS316, Inconel 625 og 718, Aluminium, Carbon Stål

21. Har bedriften din planer om selv å produsere deler ved hjelp av additiv produksjon (AM)?

1)Nei, kun leverandører vil bli brukt
2) Kun polymerkomponenter
3) Kun metalliske komponenter
4) Både polymere og metalliske komponenter

Alle planlegger å bruke leverandører for metal og kun polymerdeler fra operatørene.

22. Hvordan ser din bedrift for seg forholdet til leverandører av AM-tjenester?"

Et utvalg faste leverandører basert i Norge
Et utvalg faste leverandører i og utenfor Norge
Ingen faste avtaler, prisstyrte tilbud i Norge
Ingen faste avtaler, prisstyrte tilbud i og utenfor Norge

Et utvalg faste leverandører basert i primært Norge, men og utenfor.

23. Hvilken type metalliske komponenter ser din bedrift for seg å produsere med AM? Kryss av det som er relevant, flere alternativer kan velges.

Braketter
Tertiærkonstruksjon
Primær- og sekundærkonstruksjon
Pakninger
Boreutstyr ikke trykksatt
Boreutstyr, trykksatt
Trykkbærende komponenter i utility-systemer
Trykkbærende komponenter i hydrokarbon-systemer

Alle svarer braketter og andre ser i tillegg bruk i: Primær- og sekundærkonstruksjon, pakninger, boreutstyr, ikke-trykksatt og trykkbærende komponenter i utility-systemer. En ser i tillegg for seg deler til: Trykkbærende komponenter i hydrokarbon-systemer, trykkbærende komponenter i utility-systemer, og trykksatt boreutstyr.

Kvalifikasjon og kravspesifikasjoner:

24. Beskriv hvilke krav som vil bli stilt til kvalifikasjon av de ulike komponentgruppene som operatør ser for seg å produsere additivt.

Variasjon i svar da noen skal bruke API- og DNV-standarder mens en annen bruker tredjeparts sertifisering av komponent.

25. **Beskriv hvilke krav som vil bli stilt for kvalifikasjon og kvalitetssikring av leverandører av AM-komponenter."**

Bruk av standarder, men fra spesifikke standarder til bruk av innkjøpsprosesser med mulige leverandører. En Audit prosess er utviklet der flere operatører skal lage en guideline for hvordan AM produsenter blir kvalifisert.

26. **Har din bedrift tydelige kravdokumenter for å ta i bruk AM-komponenter og hvordan vil dette behandles relativt til eksisterende standardverk og spesifikasjoner, f.eks. materialklasse i pipingspesifikasjon, materialdatablad, etc.?**
    Beskriv hva som eventuelt mangler

Noen bygger egne fra eksisterende MDSer mens øvrige tar i bruk eksisterende standarder. Etablering av MDS i NORSOK er pågående arbeid.

27. **Er bedriften med i standardiseringsarbeid/JIP for AM og evt. hvilke standardorganisasjoner er dere involvert i?**

Deltar i generelt standardiseringsarbeid i f.eks. API 20S&20T, samt samarbeid mellom operatører.

28. **Kan du fortelle mer om andre områder dere jobber med innenfor metalliske AM-produkter?**

Noen har svart at de driver med samarbeidsprosjekter mellom operatører og bedrifter innen AM. Arbeidet går på å bygge opp en leverandørskjede. Spre kunnskap internt for å se på flere muligheter innen bruk av AM.

29. **Hvordan vil dere bidra til å bygge verdikjeder for å øke kapasitet og kompetansen innen AM?**

Noen samarbeider med andre operatører for å opprette mer komplette tjenestesystem innen AM og bruker prosjekter for å bygge kompetanse. Noen har aktiv kompetansebygging mot skoler og andre parter/bedrifter i Norge og utenfor som har roller for fremtidig økt bruk av AM.

8.3 AM Energy Network survey

A survey was made in 2023 by the **AM Energy Network** on additive manufacturing in the energy sector. This gave many interesting insights into the AM business in many ways.
The survey was comprised of multiple-choice questions with an opportunity for additional comments. They received input from 41 responders, and this was claimed to represent about "*15% of the entire AM Energy*" Network population at the time of the survey, excluding committee members.

"*The survey revealed that 90% of the respondents had already utilized additive manufacturing in either pilot/R&D projects (50%) or serial applications (40%).*"
The response from the experience of AM stated that "*90% of the respondents had already utilized additive manufacturing in either pilot/R&D projects (50%) or serial applications (40%).*"

Design freedom: The design varies between the different methods.
In the study from AM Energy a large proportion of the respondents claim the Design freedom as "*of utmost importance*", and suggests that many will, or plan to use it in new products that are designed to make use of the AM capabilities.

9 Use of AM today for offshore applications

Dental, healthcare and aerospace were early adopters of getting AM parts certified. Part size might be one of the reasons why oil and gas has been slower at adopting additive technology. However, the cost of spare parts both in procurement and warehouse has made AM a focus area for the operators. One challenge is that spreading the information on how parts are made is something that can alter the competition, and answers can be given to show that a user is making use of new technology.

- Vår Energi are sponsoring research projects to develop digital warehouses and AM knowledge. They also use internal projects on parts as a way to develop internal knowledge when ordering AM parts[79].
- Shell AM factory have set up their Energy Transition Campus Amsterdam where they have the capacity for doing reverse engineering to allow for manufacturing of both old and new parts with AM. Focus is spare parts to reduce warehouse cost and they are developing a library of digital passports to find possible spare part designs to build[80].
- Equinor together with partners are building a Digital Inventory solution with operators and Fieldnode. They aim for reducing their physical warehouse with 25% within 3-5 years [81].

SINTEF Manufacturing has little knowledge on the AM parts that have been installed and tested. We also lack the approval to include them in this report.

10 Risk evaluation

Risk is commonly defined as the product of consequences of failure (CoF) and the probability of failure (PoF). Consequences of failure may involve several categories and include damage to personnel, environment, financials and reputation. In the context of the application of AM mechanical components, the probability of failure relates to the likelihood that a part fails due to a known or unknown failure mode by a known or unknown failure mechanism.

From the preceding definition it becomes apparent that part application and quality determines risk level. E.g. an AM built part in high grade alloy 625 used for an internal valve stem of a low-pressure utility freshwater system; imposes a lower application risk than an AM built valve body of 316L subjected to high stress and pressure in a wet gas system. Examples of measures that can be put in place to mitigate risk are:

- Applications within primary barriers lower PoF, e.g. only using parts for low pressure applications with fewer degradation mechanisms.
- Applying AM parts in verified non-fatigue applications reduces PoF.
- Implementing safety factors through the design process reduces PoF.

We can deduct that risk can be controlled to an acceptable level through:

- Application control which reduces CoF.
- Material selection, testing and manufacturing control which reduces PoF.

Equinor has developed a material data sheet (MDS) for the implementation of AM-produced valve internals, see
Table 4 [82]. The application in this instance does not raise concerns as the part's criticality in the system is low. In its implementation phase, it is important that AM parts are introduced to low-criticality systems to mitigate risk. As the technology matures and the practical applications of the products are better understood, risk may be controlled to an appropriate level while increasing acceptance to CoF, e.g. using an AM part that is exposed to more degradation mechanisms as a critical component.

Concerns may at the current point in time be raised with regards to PoF. While PBF standardization has come a long way, specific standards for the material properties of DED-produced alloys do not exist. For both manufacturing processes however, standards have been developed for testing, which is discussed in section 10.1. Competence and programmes or a lack thereof is discussed in section 10.2, before section 10.3 covers the AM market and supply chains. Finally, Section 10.4 elaborates on the MDS published by Equinor and evaluates differences between standards specifically developed for AM with potential risks of referring to standards for forged material when implementing an AM part.

10.1 Risk in contrast to governing standards

The main qualification standards for additively manufactured parts in the energy industry are API 20S and DNV-ST-B203. These standards provide strict limits for qualification validity, which means that in general, the quality will be thoroughly verified through extensive testing of sacrificial parts, making the quality, and thereby the risks, associated with using additively manufactured parts comparable to the risks of using parts manufactured by conventional production methods. Most of the survey respondents have stated that they will apply one of these two standards.

Looking at the qualification standards, a main concern is changes to the deposition path. Experience with DED-LB of Duplex Stainless Steels has shown that relatively small changes to the deposition path may introduce significant defects to the part with otherwise identical process parameters. According to API20S, the deposition path is not specifically included as an essential parameter, which it is with DNV-ST-B203. It can be argued that API20S covers deposition path indirectly by listing “programmed layer thickness” as an essential parameter, but the end-users should be aware of this “loophole”. DNV-ST-B203 lists “deposition strategy” as an essential parameter, although this conflicts with the “part family” qualification range allowed by the DNV standard. A typical case would be that a slightly different component is urgently needed, and an existing part qualification is used to waive new qualification testing even though the new part will require changes from the qualified deposition path. Hence, it will be up to the end-users to ensure that the qualification testing is representative for the deposition paths employed by the suppliers of AM services for the actual part. Based on the survey results, SINTEF Manufacturing is concerned that several of the operators are not competence-wise equipped to evaluate these levels of details. A way forward could be that MDS specific for AM parts are made, where any change of deposition path requires production testing to qualify the change. Testing of a sacrificial extension would be recommended in these cases, provided that the extension captures the new part of the deposition path.

10.2 AM Competence, education and knowledge

Being a newly emerging but rapidly expanding technology, the implementation and integration of AM into Norwegian industry may be restricted by an overall lack of available education programmes. The currently $16 billion dollar industry is expected to grow to $74 billion by 2030 [83]. Across the supply chain, necessary competence needs to be held by operators, technicians, designers, supervisors, inspectors, coordinators and engineers. The international AM qualification system (IAMQS) has been developed to ensure competency in industry and is managed by the European Welding Federation (EWF). Many countries offer training through these programmes, including Portugal, Spain, Turkey, Italy, France and England. Currently, none of the Nordic countries have nominated bodies that offer IAMQS training courses, which are based on ISO/ASTM standards. Without streamlined courses of qualification it is up to each manufacturer to adequately qualify personnel. DNV-ST-B203 sets requirements to how many hours of on-the-job shadowing an operator needs go through before operating AM machinery, with suggestions to multiple choice tests that may help procure knowledge. Naturally, the extent and quality of this training will vary between manufacturers.

While IAMQS has been developed for industry and by industry with its launch in 2020, the focus that national governmental education programmes have towards AM is varied. In the integrated master’s programme in materials technology at NTNU, the first opportunity students have of being familiarized with AM is usually through the specialization project and master thesis. Furthermore, industry in Norway could benefit from the implementation of AM technology in earlier stages of education. While craft schools (Fagbrev in Norwegian) exist for trades like casting, smithing and other metal manufacturing techniques, none currently exist specifically for AM. In Norwegian vocational school elements of additive manufacturing exist, with one course called TP-PIN being under development and set to be available in 2025 [84].

The purpose of this section is not to suggest reforms in the education system, nor come with suggestions to make it better. This section simply underlines the risks associated with underqualified personnel. While the current size of the Norwegian AM market sees its needs met, future growth, the quality of parts and supply is dependent on the appropriate training and education of involved personnel.

10.3 Supply chain management

The additive manufacturing industry in Norway is young, and because of this, the supply chains for additive manufacturing are in most cases not yet established. This brings opportunity for companies to establish themselves as service suppliers, but it also creates risk since both equipment and personnel are untested, and the companies will in most cases also not be accustomed to supplying parts to the energy industry.

Most of the operators have responded that they aim to establish frame agreements with a selection of Norwegian AM suppliers. Since the additive manufacturing industry in Norway is small, this introduces the risk of insufficient competence in the supplier market. Typically, this will be managed by applying the correct qualification standards, since they cover both supplier, equipment and the supplier’s personnel. However, it is still a chance that few orders for AM material can lead to insufficient competence and experience among the suppliers, which can result in defects, delays and a driving force to accept material that would otherwise have been rejected. One way to mitigate this could be that the operators establish strategic collaborations with not just the AM suppliers, but also between themselves to identify which suppliers they intend to use for which materials and parts. In this way, the suppliers can receive a steady supply of assignments that will keep them in business and lead to increased knowledge, experience and specialisation among the Norwegian AM suppliers.

Risk of insufficient competence in the operator organisation with procurement and schedule driven procurement processes: There have been relatively few projects where AM components have been used for critical applications on the NCS. This far, the operators have been heavily dependent on competence from the AM suppliers for almost all AM fabrication specifics, while the AM suppliers have depended on materials technology competence from the operators. In most cases, this gap has been covered because the necessary total competence has been available. However, it may not always be clear for the operator if the supplier’s experience is insufficient, and the operator may not have the necessary competence to complement the supplier, or the necessary competence may not be made available to the supplier when required. In theory, this risk would be covered by the AM qualification standards, but defects and delays will always be unfavourable since they will often create motivation to deliver and accept substandard material.

It has been observed that Norwegian AM companies have voiced concerns about qualification according to energy industry standards, mainly DNV-ST-B203. To some extent, this is understandable, since several of the AM companies consist mainly of equipment operators, with limited background in materials technology. Because of this, they are often operating AM machines in accordance with recommendations and requirements from the machine manufacturer, often also utilising feedstock from the machine manufacturer to produce material with “guaranteed” properties. With this backdrop, it is easy to understand that build process qualification and part qualification can seem excessive, especially if the AM service provider is expected to cover all costs associated with the qualification. On the other hand, since the qualification will belong to the AM service provider, it will often be expected from the operators that the service providers are willing to absorb that cost, and it will be challenging for the operators to accept the use of AM material if the qualification standards have not been met. To bridge this gap, it will be necessary that the operators assess actual criticality, and do not add requirements unnecessarily. In addition, the AM service providers will need to accept that parts with higher criticality will require more qualification testing, and their prices must be adjusted to reflect this for the parts where additional costs are incurred.

Looking outside Norway, Shell has developed their own AM centre, where they operate AM machines to produce spare parts in-house. This is a way to manage supply chain risk since they can have more control of both competence and machines. Still, there is a risk that projects and prestige can overrule the technical aspects of quality, and it does in no way guarantee that the supplied material will meet all requirements. Some of the Norwegian operators have informed that they intend to produce polymer parts with AM in-house, but none have plans for AM of metallic materials. This means that for most practical applications, the criticality of the in-house produced AM materials among the Norwegian operators will be relatively low.

10.4 Lack of MDS and standards for AM

While AM has matured in aerospace and medicine industries, the adoption of this technology has been limited in the oil and gas sectors [85]. The Norwegian offshore industry is characterized by a strong focus on risk mitigation, which in part is offered by easily accessible standards, recommended practices and material data sheets. At the current point in time, a lack of available standards may make it challenging to create MDS for components for use offshore.

Below in

Table 4, is a summary of information in MDS XA501 published by Equinor. This is the only MDS they have published with regards to AM. Applicable standards, production methods, materials and required heat treatment is listed. All qualification tests are introduced with a basis in DNV-ST-B203 and API 20S, but additional testing and requirements are specified in some instances.

Table 4: MDS XA501 developed by Equinor for AM valves [82]

MDS XA501 for AM produced valve internals used offshore			
Material	**Production method**	**Applicable standards for material properties**	**Necessary heat treatment**
Alloy 625	PBF or DED	• PBF: ASTM F3056 • DED: ASTM B564 grade N06625	Annealing or solution annealing
Alloy 718	PBF or DED	• PBF: ASTM F3055 • DED: API 6A CRA	None
CP Titanium Grades 1-5, Ti-6Al-4V Grade 23 Ti and Ti-6Al-4V Grade 5	PBF or DED	• PBF: ASTM F3302 • DED: ASTM B381, grade F-1, F-2, F-3, F-5 or F-25	Stress relieving, HIP or annealing

316L	PBF or DED	• PBF: ASTM F3184 • DED: ASTM A182	Solution annealing
25Cr Super duplex	PBF or DED	• PBF: Composition and mechanical properties according to ASTM A182. Impact testing, microstructural analysis and corrosion properties according to ISO17781 • DED: Composition and mechanical properties according to ASTM A182. Impact testing, microstructural analysis and corrosion properties according to ISO17781	Solution annealing and quenching
22Cr Super duplex	PBF or DED	• PBF: Composition and mechanical properties according to ASTM A182. Impact testing, microstructural analysis and corrosion properties according to ISO17781 • DED: Composition and mechanical properties according to ASTM A182. Impact testing, microstructural analysis and corrosion properties according to ISO17781	Solution annealing and quenching

DNV-ST-B203 explicitly states that care should be taken when applying standards for other manufacturing methods on metals produced by AM. SINTEF Manufacturing has therefore conducted a comparative analysis between ASTM A182 “Standard specification for forged or rolled alloy and stainless steel pipe flanges, forged fittings, and valves and parts for high-temperature service” and ASTM F3184 “Standard specification for additive manufacturing stainless steel alloy (UNS S31603) with powder bed fusion”. The following list points out the most important differences.

- ASTM F3184 sets stricter requirements for tensile properties than A182, with UTS and yield strength being higher. Furthermore, it requires these properties to be the same in three different tested directions, whereas A182 only requires one direction. Note that A182 incorporates a variety of alloys, and that many alloys within the 316 group have the same requirements to UTS and yield strength as F3184. A182 sets stricter requirements to area of reduction.

- Many supplementary requirements are found in ASTM F3184 that cover but are not limited to, impact tests, microstructure and component density. These are not covered by A182 but with a basis in API 20S or DNV-ST-B203 these will have to be tested for regardless. ASTM F3184 sets no explicit requirements but leaves this up to purchaser and supplier.
- ASTM F3184 recommends fatigue testing when components are subjected to dynamic loading. This is not covered by A182.
- A182 sets requirements for surface finish. ASTM F3184 simply states that this may be important due to inherent differences in PBF produced material.
- A182 does not require detrimental phase detection. ASTM F3184 leaves “microstructural analysis” up to purchaser and supplier without explicitly referencing detrimental phases.

While ASTM F3184 incorporates more supplementary requirements than A182, these are adequately covered by API 20S and DNV-ST-B203. Furthermore, these supplementary requirements are often lacking in detail, and simply give the purchaser and supplier a notion of what tests can be done without explicit demands to property. It is therefore crucial that relevant competence is held by both supplier and operator when referring to these standards and setting additional requirements through an MDS. Naturally this might be a significant barrier to implementing an AM supply chain due to uncertainty surrounding necessary testing and the ease of which a product can be certified.

Flexible and loosely defined standards may increase PoF in cases where sufficient knowledge has not been established by manufacturer and operator. E.g. ASTM F3184 requires microstructural analysis but does not provide acceptance criteria for quantities of detrimental phases. The manufacturer and purchaser can reduce risk through conservative requirements, with the downside of potentially useful components meeting too stringent demands. An analogy can be made to how NORSOK first detailed the microstructural requirements for cast and wrought Duplex. Initially, the demand was set to parts having no intermetallic phases or precipitates at 400X, which manufacturers struggled to satisfy. Since then, alternative acceptance criteria have been established through e.g. NORSOK M630, in which a Charpy impact test result can be used to accept material containing detrimental microstructural constituents. Experience shows that good production standards are a result of time and “round robin” cooperation agreements. SINTEF Manufacturing believes that current AM standards need to establish realistic acceptance criteria for supply chains to be easily established, while maintaining risk at an appropriate level.

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