Wire-based direct energy deposition (DED) applications in maritime industry

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Abstract

Maritime industry plays a significant part in the world's economy, because around 90% of all goods in the world are transported by shipping at one point. Therefore, finding ways to improve the performance of different components and cut the manufacturing times of these components is vital to enhance the efficiency and profitability of the entire branch. Incorporating wire-based direct energy deposition (DED) methods could cut manufacturing time, costs and decrease the required manpower, whilst creating parts with great mechanical properties and complex shapes and dimensions. DED processes can also be implemented with smart systems and sensors, which can track different parameters of the substrate during the process and make slight changes to parameters, such as power or feed rate of the wire.

The parts that can be fabricated by DED are ones that are difficult or expensive to manufacture using traditional methods, such as sand moulding. To fabricate these parts with moulding would require high heat input, increased costs and material losses. The repeatability of the traditional processes is relatively poor due to the single-use nature of the moulds in sand moulding. The manufactured components are usually parts that have complex shapes, such as propellers, need to withstand corrosion, such as parts of the hull and need to withstand heat and fatiguing, such as parts of the engine. DED processes can fabricate components from scratch or even repair parts that otherwise would have to be replaced with little losses to mechanical properties, such as tensile strength.

The wire-based DED methods examined in this thesis are wire-arc additive manufacturing method (WAAM) and laser-based direct energy depositions (DED-LB). The working principle of both processes are that a heat source creates a melt pool and a feedstock material, in this case wire is added to create a substrate. This process is repeated several times to create a 2D/3D object. WAAM and DED-LB vary from each other by the speed of the fabrication process or the quality of the end product. The goal of this thesis is to explain the fundamental differences between WAAM and (DED-LB) and how both can be applied to the maritime industry.

Merenkulkuteollisuudella on huomattava rooli maailmantaloudessa, sillä noin 90 % kaikesta tavarasta kuljetetaan laivalla jossain pisteessä. Täten on tärkeää löytää menetelmiä, joilla parannetaan eri komponenttien suorituskykyä sekä vähennetään näiden komponenttien valmistusaikoja, jotta koko toimialan tehokkuus ja kannattavuus paranee. Lankaperäisen suorakerrostusmenetelmän (DED) sovittaminen voi leikata valmistusaikoja, kustannuksia sekä vähentää työvoiman tarvetta samalla luoden osia, joilla on hyvät mekaaniset ominaisuudet sekä monimutkaiset muodot. DED prosesseihin voi myös soveltaa älykkäitä järjestelmiä ja sensoreita, jotka voivat seurata kerrosten eri parametreja prosessin aikana sekä tehdä pieniä muutoksia eri parametreihin, kuten tehoon sekä langansyöttönopeuteen.

Osat, joita voi valmistaa DED:lla ovat monimutkaisia tai kalliita valmistaa käyttämällä perinteisiä valmistusmenetelmiä, kuten hiekkavalamista. Näiden osien valmistaminen valamalla vaatii korkeita lämpötiloja, lisäkustannuksia sekä aiheuttaa materiaalihäviöitä. Perinteisten valmistusmenetelmien toistettavuus on melko huono johtuen hiekkamuottien kertakäyttöisyydestä. Valmistetut kappaleet, kuten potkurit ja laivan rungon osat ovat muodoltaan monimutkaisia sekä niiden pitää vastustaa korroosiota, sekä kappaleiden tarvitsee vastustaa lämpöä sekä liikettä, kuten moottorin eri osat. DED prosessit voivat luoda osia tyhjästä tai jopa korjata osia, jotka pitäisi kokonaan vaihtaa samalla kärsien vain pieniä tappioita mekaanisiin ominaisuuksiin, kuten vetolujuuteen.

Lankaperäiset DED menetelmät, joita tutkitaan tässä tutkielmassa ovat wire-arc additive manufacturing method (WAAM) sekä laser-based direct energy deposition (DED-LB). Molempien toimintaperiaatteet ovat, että lämpölähde luo lämpöalueen, jonka jälkeen lisäaine, tässä tapauksessa lanka lisätään luoden kerroksen.

Tämä toistetaan usean kerran, kunnes 2D/3D kappale on luotu. WAAM ja DED-LB eroavat toisistaan prosessin nopeudella sekä lopputuotteen laadulla. Tämän tutkielman päämäärä on selittää olennaiset erot WAAM:n ja DED-LB:n välillä ja miten molempia voi soveltaa merenkulkuteollisuuteen.

Key words: Wire-based DED, maritime industry

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1. Introduction to wire-based DED

Metal additive manufacturing (AM) can be considered as an emerging manufacturing form. This capability is achieved due to the process' versatility, mechanical properties and dispatch rate of the used material [1]. Due to its versatility AM can be used in a large variety of fields, for example, maritime, aerospace and construction industry. AM can also be applied to repairing and manufacturing different components and structures.

Direct energy deposition (DED) is a branch of additive manufacturing. The working principle of DED is that a feedstock material is applied to a surface and the material is melted using an energy source whilst inert gas protects the melt pool from atmospheric gases. The design for the structure comes from a computer aided design (CAD) file, which is inserted into the DED system. Many DED systems employ an automated robot arm, which processes the CAD file and starts the fabrication process by laying and melting the feedstock material. This melt solidifies and more layers are then stacked on top of each other to create a three-dimensional structure [2]. The methods used in this process can be divided into several sub-categories and the feedstock material can be wire- or powder-based. A wire-arc additive manufacturing (WAAM) robot can be seen in Figure 1.

Figure 1 WAAM robot arm (left) and its MAG-welding type nozzle head (right) in Koneteknologiakeskus, Turku, Finland

In powder-bed DED the powder is inserted into the surface, after which the energy source, usually a laser, melts the powder into a hard surface. This process is then repeated on top of said surface with the aim of creating a three-dimensional object. Wire-based DED differs from powder-based DED by the feedstock material, nature of the melt process and mechanical properties of the finished product [3]. The working principle of powder-based DED process can be seen in Figure 2.

In wire-based DED the wire is inserted straight into the melt pool created by the energy source. The material melts and solidifies on a surface after which the process is repeated to create a structure. Both processes follow the design created by a CAD-created design. Although the powder-based DED can create objects with finer surface quality and more complex design, it comes short compared to wire-based DED in material consumption and manufacturing speed, which makes wire-based DED more applicable to fields with high demand for large components [3].

Direct energy depositions are also divided into categories by the applied energy source. The creation of the melt pool can be accomplished by using wire-arc AM (WAAM) or laser-based DED (DED-LB). These processes vary in terms of manufacturing speed, surface quality and feedstock material. These properties also dictate the fields that these processes are mainly used in. [2]

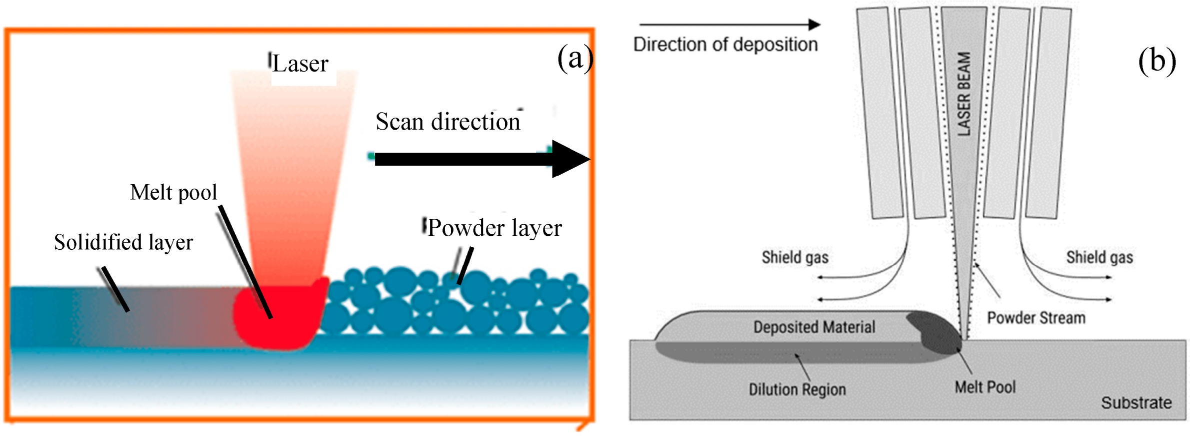

Figure 2 (a) Powder-bed fusion and (b) simplified powder-bed fusion process.[3]

1.1 Laser-based DED (DED-LB)

1.1.1 DED-LB process

Laser-based DED is an additive manufacturing process, where the melt pool is created using a laser from a powder- or a wire-based feedstock material. The most common wire-feeding process involves the wire being fed in front of the laser and the laser melting the wire. After a predetermined distance, the wire is fed and melted on top of the created substrate to create a three-dimensional object. Also, a shield gas is used to prevent the melted material from oxidation due to atmospheric gases. [4]

A second option for the wire laying is coaxial wire feeding, where the wire is fed straight from the laser nozzle into the melt pool. However, the laser beam is separated behind the wire, mirrored towards the melt pool and concentrated into the melt pool using a lens, where the wire is being fed.

Although the wire and laser beams are fed and projected from the same nozzle, they don't converge with each other before the melt pool due to the laser beam being situated at the periphery of the nozzle. Coaxial wire feeding ensures more homogeneous melting of the wire. Linear and coaxial wire-feeding processes can be seen in Figure 3. [4]

There is a wide variety of different wire materials that can be used in DED-LB that vary in cost, field of use and mechanical properties. According to Saboori et al. (2019) these materials can be: "Monolithic stainless steel, aluminium, titanium, nickel and copper alloys". Also, the wire can also be a bimetal, which is a mixture of two metals. These bimetals are often steel mixed with one of the aforementioned metals in order to combine different mechanical abilities of the two metals. This can also be applied in structures that has different continuous parts made from two different metals. [3]

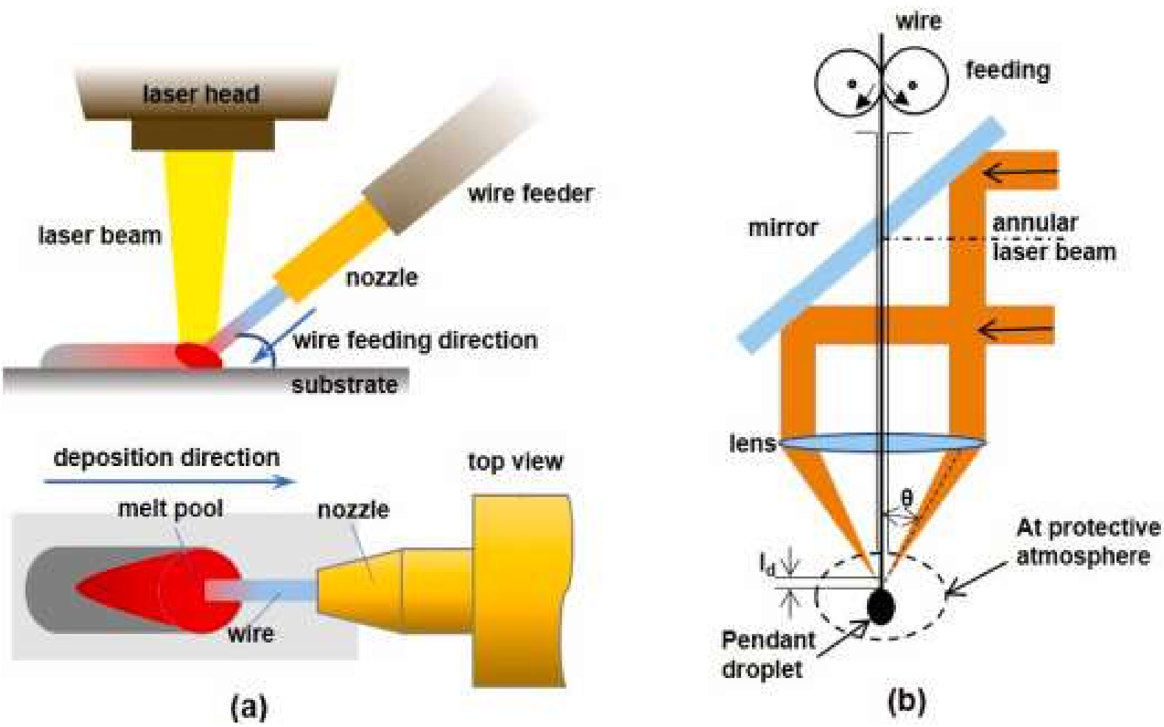

Figure 3 (a) Linear wire feeding (b) Coaxial wire feeding. [4]

1.1.2 Attributes

Wire-based DED processes have great feedstock material efficiency in general. Unlike powder-based processed, where some amount of the used powder goes to waste, the wire-based process has almost 100 percent materials efficiency due to the wire being directly inserted into the energy source. Therefore, laser-based DED can be considered as a relatively efficient process. Since laser directly applies heat to the wire, and the wire melts just enough to bind to the layer below, DED-LB creates small heat affected zones (HAZ), which means that heat optimization is easier. This also enables the process to have a high precision and little change to the bottom layer's microstructure, because the energy is subjected almost entirely into the feedstock material. The melting process also ensures that the object is overall dense, because the bonding between the feedstock material and the melted layer is uniform and strong. [2]

DED-LB also has a positive impact on the mechanical properties of the melted material. Usually with conventional manufacturing methods, such as moulding, there are high residual stresses and distortion involved in the material after processing. However, DED-LB has produced materials that have had minor amount of distortion in structures due to the low HAZ and the concise melt area. Parts repaired or manufactured with DED-LB mostly maintain their attributes, such as corrosion resistance, conductivity, thermal and mechanical properties. The mechanical property losses, in this case tensile strength, can be seen in an article by Saboori et al (2019) in which a test was conducted, where a cast iron part is repaired using DED-LB. As seen in Figure 4, the tensile stress does decrease after being repaired by DED-LB, but due to the small HAZ the cast iron yields less making it more resilient [3]. Lastly, the number of different materials that can be processed with DED-LB is vast. Alongside metals other materials, such as polymers, composites and ceramics can be produced, which makes DED-LB versatile. [2]

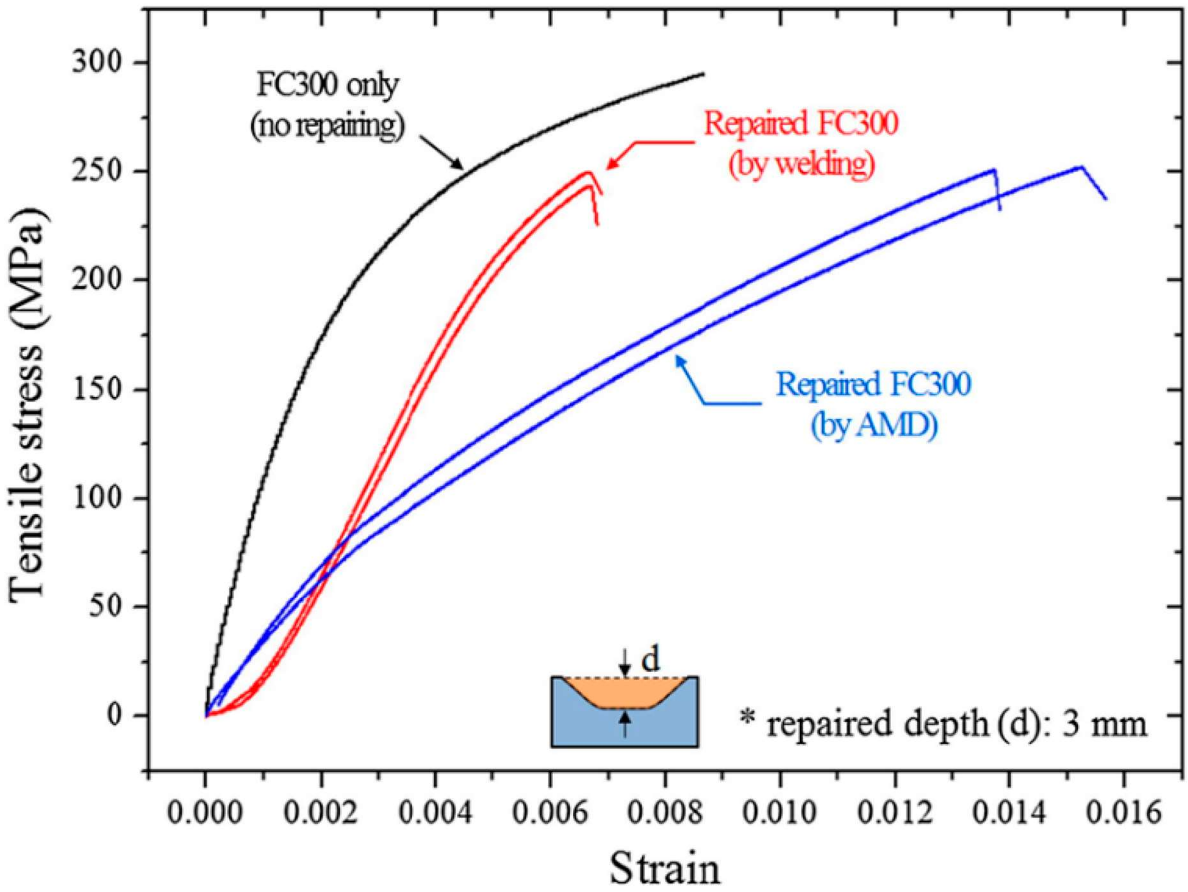

Figure 4 Stress-strain curve of cast iron repaired by welding and DED-LB [3]

Laser-based DED also has some drawbacks. Firstly, the process is relatively slow due to solid metal wire requiring more energy to melt. According to Li et al (2022), the wire-feeding speed into the melt pool is 0,5-5m/min. This article included a study where a titanium alloy was used at which the wire diameter ranges from 1-1,2mm, feeding speed of 1000-4200 mm/min and laser power ranging between 1200-3500 Watts. These variables considered, the process reached deposition rates between 30-285 cubic centimetres in an hour, making the process slow, but faster than laser powder bed fusion (LPBF), which has deposition rates between 2-65 cubic centimetres in an hour [4]. Although higher speed and power can be used, these high parameters also have a negative effect on the efficiency of the process and the surface quality of the structure. The surface roughness in DED-LB process is between 60 to 100µm [5]. High surface roughness means that the structure may need to be post-processed, which takes time and resources. Additional problems with the structures created with DED-LB are relatively high residual stresses, which must be taken into account during the manufacturing process, or it might risk damaging the structure, when the hot substrate cools [3].

Many disadvantages to DED-LB come from the design and financial standpoint. Due to still being relatively niche manufacturing process, machinery and implementation costs of DED-LB are relatively high compared to the overall output that can be created with it. The design standpoint is affected due to the slowness of creating CAD-models. Because the products created with DED-LB are mostly specialized products means that new CAD-models must be often created to manufacture new products, which hinders the process even more. However, the cost and design drawbacks will most likely be mitigated, when the process becomes more advanced and widespread [6].

1.1.3 Industry applications

Currently, DED-LB isn't yet a widely adapted in mass manufacturing. However, due to its ability to repair difficult defects, such as broken metallic blades, crevices and different complex parts it is useful in reducing costs by fixing broken parts instead of fully replacing them. This means that turbine blades that are missing a chunk of metal doesn't have to be fully replaced, because the blade can be repaired using DED-LB. Also, DED-LB can be applied in fields that require low to medium-sized specific parts. These fields are, for example, maritime industry with engine and propeller parts, aerospace with turbine blades and construction sector with different structural components, such as beams [1]. In Figure 5, a DED-LB module, its work process and structures created from different materials can be seen.

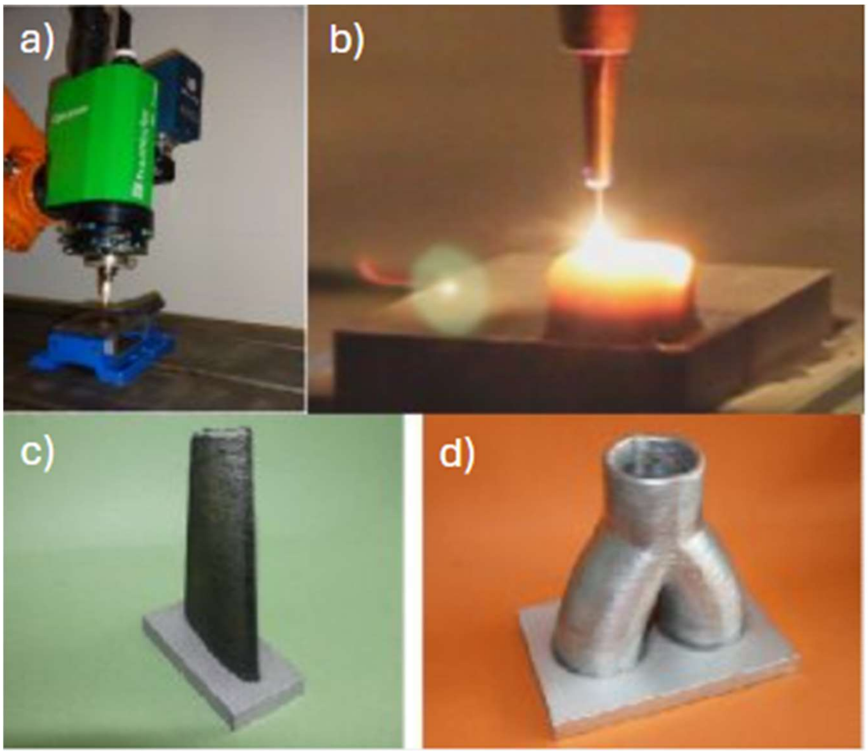

Figure 5 (a) DED-LB module (b) work process (c) Inconel 718 turbine blade (d) AlMg5 inlet tube [5]

1.1.4 Case study

A study was conducted by Hamilton et al (2023), where a grey cast iron (GCI) part was repaired using powder- and wire-based laser DED. GCI is most often used to repair damaged engine parts in the agricultural industry, but it can be applied to several other fields, such as maritime or automotive industries. The feedstock materials used for the repair were stainless steel 316L (SS316L) and Inconel 625 (IN625), which is a nickel-based superalloy. The research was conducted by repairing a groove on a GCI block with DED-LB and post-processed in order to conduct a strength test. The CAD-created designs can be seen in Figure 6. [7]

Four variables were measured after the repair: microstructure, microhardness, porosity and tensile strength. The microstructure of SS316L showed some fractures and sporadic formation of martensite. IN625 samples showed some failures of fusion between GCI and IN625 crevice and some formation of martensite along the crevice line. In the microhardness test the microhardness was uniform along the repair line. Microhardness towards the normal of the repair line showed some spikes due to the formation of martensite along the border between the feedstock material and GCI. In the porosity measurements it was determined that both feedstock materials formed few pores due to the large melt pool. The tensile test showed some dispersion between SS316L and IN625. By using SS316L as the feedstock material the strength of the GCI was regained by 97,7%. With IN625, the strength was restored by 85,9%. [7]

This study proves that DED-LB is a reliable repair process. Although there were some changes in the microstructure and some losses to tensile strength, the method can still be considered as a reliable, safe and cost-effective in the long run.

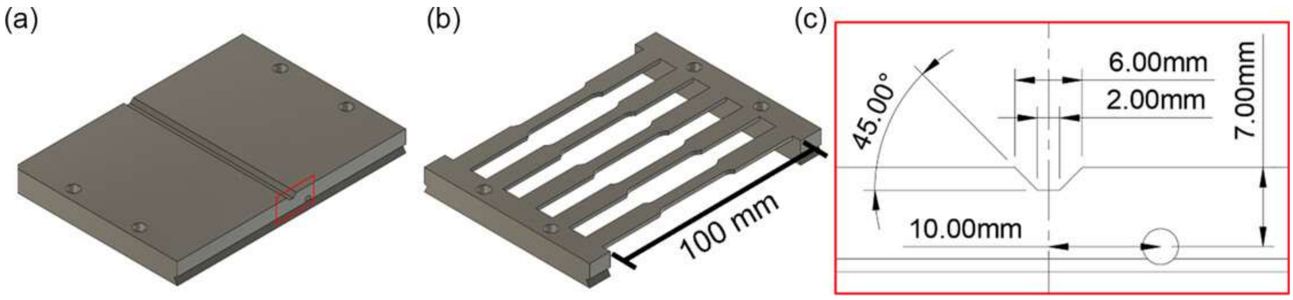

Figure 6 CAD drawings of (a) Sample before remanufacturing (b) after deposition and post-processed (c) dimensions of the groove [7]

1.2 WAAM

1.2.1 WAAM Process

WAAM is a DED process, where an electric arc is used as the energy source to create a melt pool [8]. Similar to welding, WAAM uses gases to protect the melt from oxidation due to atmospheric gases. In WAAM, the wire material can differ and thus structures with varying mechanical properties can be created. Some feedstock materials used in WAAM are different titanium-, aluminium- and iron-based alloys. Structures constructed with WAAM have reached relatively high hardness levels, have had great stress distribution and great microstructure [9]. The WAAM process shares many similarities with welding, because the electric arc used is often the same welding arc that is used in existing welding technologies. The WAAM process can use MIG (metal inert gas) welding, where an electric arc forms between the nozzle and the working surface, which melts the feedstock material coming from the nozzle. Tig-based process can be used, where the feedstock material is added from a separate head and the electric arc melts it. Also, a plasma-based PAW (plasma arc welding) method can be applied, which uses plasma as heat source. Simplified WAAM process can be seen in Figure 7 [10].

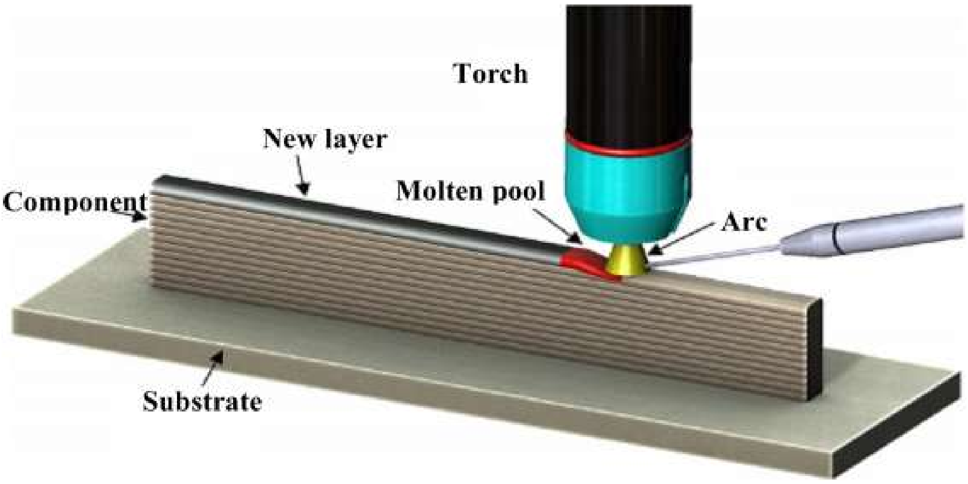

Figure 7 Schematic of the WAAM process [10].

1.2.2 Attributes

Many DED methods can be considered relatively slow, but WAAM can be considered faster than powder-based DED and DED-LB. This is mostly because of the high heat input that is employed in the WAAM process. Although the amount of energy directed into the melt pool changes in regards of the feedstock material, the overall energy input stays relatively high. This allows higher deposition rates (around 4-9kg/hr [6]) which opens the opportunity for WAAM process to create large structures faster than DED-LB. The construction of these customized large structures is also relatively cheap compared to other powder- and wire-based AM techniques. [10]

Similar to DED-LB, WAAM has almost 100 percent material efficiency, because the energy is directed fully to the feedstock material and because the wire is uniform and receives constant amount of energy, the whole feedstock material is utilized. High material efficiency also leads directly to lower material costs, which apart for the acquisition costs for the machinery makes the process relatively cheap. [10]

Mechanical properties, cost and flexibility also depend on the electric arc generation type. The MIG-based method can be considered as a cheap method, due to the lower equipment costs and great efficiency. MIG-based method is also flexible and it’s able to reach more welding positions. This flexibility comes in very useful as can be seen in Figure 8 where the effect on the process parameters is most dependent on the angle of the torch, which gives MIG-based WAAM an advantage. However, TIG-based WAAM has better mechanical properties compared to MIG-based WAAM. TIG-based WAAM has low porosity, which means that the TIG-based method doesn’t trap as much inert gases in the substrate during manufacturing. The low porosity has an effect on the mechanical properties, because the material doesn’t have as many pores and crevices in its microstructure. [10] [11]

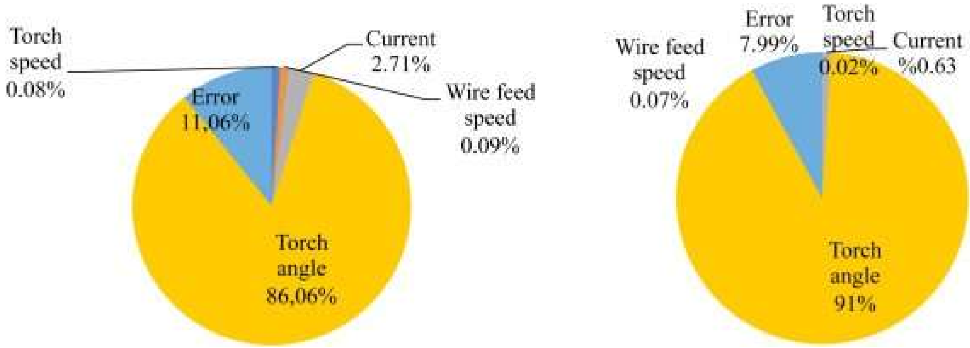

Figure 8 Effects on process parameters when (a) change in deposition width and (b) change in deposition height [10]

WAAM process faces many similar challenges to DED-LB. However, due to the higher energy input and deposition rate, the disadvantages faced in WAAM seem more extreme compared to DED-LB. Due to the high amount of energy applied to the feedstock material, the residual stresses stay high when the material cools, which causes distortion and deterioration in the finished structure [10].

Due to WAAM applying welding-based technology in its melting process, it also faces some challenges that are also faced in welding. One large problem with the WAAM process is the relatively substandard surface quality and resolution, which is only around 0,5mm [6]. In Figure 9 the surface quality of objects created with WAAM can be seen. Lastly, according to Ding et al (2015), compared to DED-LB, which has a deposition pass width of 0,7 mm, the WAAM process has a deposition pass width of 4 mm. Also, due to the nature of the process, the height of a substrate might be larger at the beginning than at the end. This creates a ramp for the molten metal to flow, which causes defects in surface geometry. [12]

Figure 9 Circular and square hollow tubes created from stainless steel with WAAM [6]

WAAM also faces problems with porosity, inadequate melting of the material creating gaps and contamination [13]. Due to the problems with distortions and surface quality, it is an utmost importance to carefully design WAAM processes. Many factors must be taken into comparison, such as wire feed rate, wire material and layer thickness, but due to the high speed of the process and great mechanical properties, WAAM has the opportunity to be applied to several manufacturing fields as a reliable process [12].

1.2.3 Industry applications

Like DED-LB, WAAM isn't yet widely adapted into mass manufacturing, and its usage still lies in the repair and manufacturing of complex and specific components. The chance to create complex parts and use wide range of materials has created an opportunity to manufacture parts that were previously created from weaker, less dense material can now be replaced by stronger, more durable materials. This can be seen in aerospace industry, where miscellaneous parts, such as hinges and connectors can be created with titanium, yet their weight could also reduce in the process, which saves on material usage and sinks costs. This can also be applied to the automotive field and medical field, where complex parts from various materials need to be manufactured [10]. An example of the limitations reached by WAAM is a pressure vessel. This pressure vessel was produced by Andritz Savonlinna Works Oy and the Finnish Additive Manufacturing Ecosystem (FAME), and it has diameter of 900mm and height of 1600mm and weighs 300kg. This design shows that heavy components with complex dimensions and high regulations can be created, which opens the door for implementing WAAM to commercial manufacturing. The pressure vessel can be seen in Figure 10. [14]

Figure 10 Pressure vessel created by Andritz Savonlinna works oy and FAME [14]

WAAM's ability to create medium to large objects has been applied to several fields. In theory the build dimensions that can be reached by WAAM are limitless, but singular parts are usually up to 2 meters in all dimensions as seen in the Andritz Savonlinna works oy example, which was one of the largest structures created with WAAM in Europe. Due to the high deposition rate, various sized objects can be created relatively quickly. This in addition to the fact that structures created with WAAM are relatively sturdy means that additional supporting structures aren't needed. An example of this kind of structure from Buchanan and Gardner (2019) is a pedestrian bridge built with

WAAM, which is located in Amsterdam (Figure 11). The bridge is made from stainless steel and it's 2.5 meters wide, 10 meters long and weighs 4500kg. These structures also need to be post-processed due to the subpar surface quality, which does take more time and resources. [6]

High demand for WAAM can also be found in the maritime industry. Due to the ability to create complex large parts from varying materials opens doors for the wide implementation of WAAM in maritime industry. Many curved hull parts can be created from aluminium and titanium depending on the strength requirements. Also, moving parts such as propeller blades can be constructed on demand in relatively short time, which cuts costs and wait times. Wider implementation of WAAM in different industries is only a matter of time now. [15]

Figure 11 MX3D bridge created with WAAM [6]

1.2.4 Case study

WAAM can also be used to combine various mechanical properties together and create an optimized performance. For instance, a study conducted by Squires et al (2023) uses WAAM to create a bimetallic structure. The materials used in this process are stainless steel 308L (SS308L) and low carbon mild steel (MS). The structure is created by using a dual-deposition device with two nozzles, which creates a hollow round casing from the mild steel and immediately fills the middle of the casing with SS308L. These layers are stacked until the structure is sufficiently large. This structure is then machined in order to reach the desired parameters. Also, a second similar object is created, and a hole is drilled in the middle of it. The object is a cylinder, diameter of which is around 10 millimetres and height around 20 millimetres. Also, two control groups of cylinders made purely from the two aforementioned metals are created and the manufacturing process can be seen in Figure 12. [9]

Four variables are analysed and measured during this study: microstructure before and after a compression test, hardness test and compression resistance. The microstructure before the compression test shows distinct lines and great bonding between the two metals. Some impurities can be found within the material, such as chrome, nickel and ferrite. After the compression test several voids can be detected in the interface. The drilled specimen showed severe deformation in the core. The hardness values were collected horizontally across the phase of the specimen. The average hardness in the cylinder was 260 HV with a standard deviation at top 36 HV, middle 26 HV and bottom 39 HV. Hardness does vary a lot between the largest value 394 HV and lowest value 234 HV, however, compared to other tests, this variation isn’t large. A compression test was conducted to all the four objects. Most deformation was observed in both control groups, and significantly less in the bimetallic cylinder. MS control group averaged 370 MPa, SS308L 346 MPa, bimetal 493 MPa and drilled bimetal 350 MPa. This shows significant increase in compression yield strength for the bimetallic cylinder. [9]

The results and opportunities demonstrated by this study were significant. The material exhibited convincing metallurgical properties and bonding between the metals. The interface between SS308L and MS stayed consistent during the entire length of the cylinder. Any possible downsides caused by the impurities were disproven in the compression test, which resulted higher than expected results. The undrilled object also showed great hardness levels. Other conclusions drawn from this study were that the material resisted crack propagation well and the drilled specimen showed a 28% decrease in residual stresses compared to the undrilled specimen. This study proves that bimetals created by WAAM can be applied to different fields that might require material created from bimetals, such as the wind energy or the railway industry. [9]

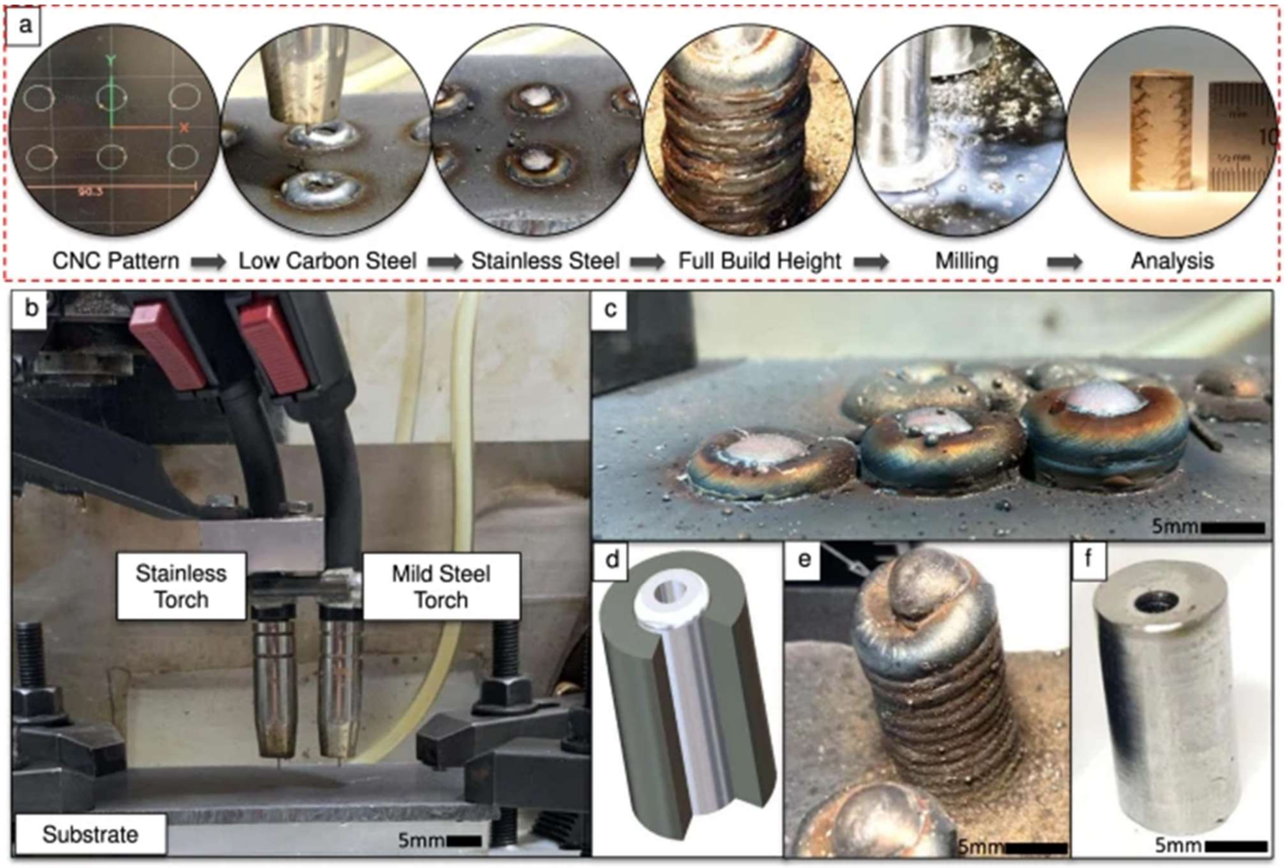

Figure 12 (a) manufacturing process (b) WAAM setup (c) structures during manufacturing (d) 3D-model (e) complete deposited cylinder (f) machined and drilled cylinder. [9]

2. Applications in maritime industry

2.1 Background

The maritime industry can be considered as the most important field in terms of transportation quantity, because almost nine tenths of all goods around the world are transported by shipping, which creates high demand for the manufacturing and repair of ship components. However, the traditional methods, such as welding and moulding of large components, such as propellers and engine parts is a process that requires huge amounts of manual labour, materials and time. Therefore, eliminating these drawbacks is an integral part of improving the industry as a whole. The implementation of AM is a potential solution for this problem, because AM can create products with great mechanical properties, low material losses and flexible structures relatively quickly with little need for manual labour. This is why AM processes, such as WAAM and DED-LB are considered the future of manufacturing in the maritime industry. Figure 13 shows the main parts of a ship that are considered in this study for AM production. [15]

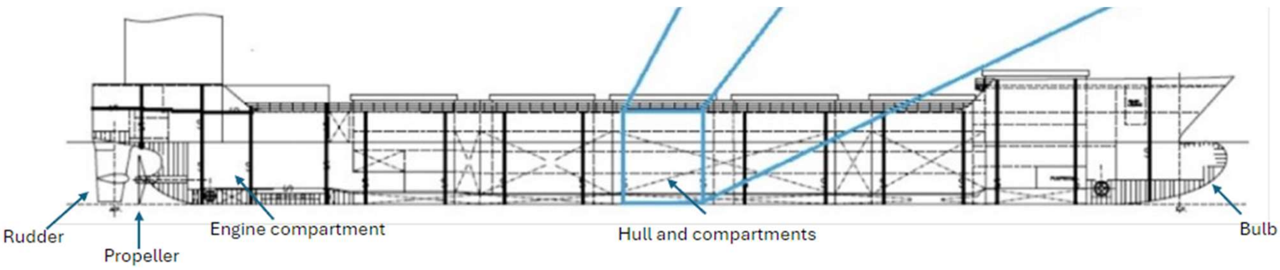

Figure 13 Ship parts considered in this study [15]

2.2 Different material implementations

The maritime industry has a high demand for materials with different mechanical properties due to the complexity of the structure and the moving parts of the ship. Many parts are required to be resistant to corrosion due to being in contact with saltwater and resistant to fatiguing due to constant rotating, such as engine parts and the propeller.

Nickel- and bronze-based alloys are used in rotating parts, such as propellers due to the resistance to seawater corrosion. An example of a bronze-based alloy is nickel-aluminium-bronze (NAB), which in addition to great corrosion resistance has excellent mechanical properties. NAB is used in several parts of the ship, such as propellers, pumps and different fixtures under the water level. Usually ship propellers are manufactured from brass but NAB has different properties that exceed brass. According to Shen et al (2018): “Compared to conventional brass propellers, the density and resulting rotation inertia of NAB propellers is 15%-19% lower, which improves carrying capacity of marine propulsion system." WAAM and DED-LB are both suitable for utilizing NAB in construction and repair. This is thanks to the full utilisation of materials and the flexibility of the process. WAAM and DED-LB would also cut different phases from production and the possibility to manufacture large quantities with only a singular CAD model. An example of a part created with WAAM, and part created with traditional casting method can be seen in Figure 14, which shows that large parts can be created with WAAM, but they have to be post-processed as shown in the figure. [16]

Figure 14 NAB-based part created with casting (left) and WAAM (right, post-processed) [15]

There are also several alloys that can be used for the same purpose as NAB but have been produced specifically for high wear tasks. An example of this is a superalloy called Inconel 718, which is regarded as one of the most reliable superalloys, due to its high strength, high fatigue life endurance and high heat resistance. However, the downside with Inconel 718 is the challenges in using traditional manufacturing methods such as cutting and machining to create complex geometries due to the hardening behaviour of the material. DED methods could solve the problem with Inconel 718, because the flexibility of DED methods allows them to access points of the structure and create substrates, which would be difficult to manufacture using traditional moulding or machining methods. Lastly, Inconel 718, NAB and other similar alloys face problems with fretting, but an easy solution is to repair the parts with different DED methods. [17]

Due to the high stresses faced by the constant mechanical wear conducted by several moving parts, engines have a requirement for materials with high tensile strength and high fatigue resistance. Also, the need to repair these parts on demand is a high priority in the maritime industry due to new parts requiring long time to manufacture from scratch. The common material used for engine parts, such as the engine block is grey cast iron, which in addition to the required mechanical properties has a low cost. However, compared to other alloys, cast iron isn't a performing one in terms of facing fatiguing and damage in use, which is why the constant repair of grey cast iron parts is a large priority. This is why AM processes are great way to manufacture and repair grey cast iron parts, because of the low heat input focused onto the material. Other iron-based materials have also been proven to be useful in the repair of grey cast iron parts, such as stainless steel, which could overall improve many properties of the material. [18]

Iron-based materials, such as different steels, especially stainless steels can be implemented due to their high levels of hardness, tensile strength and resistance to corrosion. However, stainless steel is harder to manufacture and requires more heat input, which might cause high residual stresses or worse surface quality. An example of a type of steel, which can be implemented is stainless steel 316L (SS316L), which is commonly used in different industries. SS316L can be used in parts of the ships that need to withstand fatiguing, such as the hull or different engine parts, which additionally need to withstand heat. [19]

Another material, which could be applied to the maritime industry is titanium. The main property of titanium is that it has high strength in addition to being relatively lightweight, which is why it can be applied to reinforce structures. Drawbacks of titanium are the difficulty to create complex parts, high material cost and the oxidation of titanium during machining processes. These drawbacks can be solved by applying WAAM into the manufacturing process. As mentioned before WAAM can create complex parts and has almost 100 percent material efficiency, but additionally WAAM can prevent oxidation by applying shielding gas during the manufacturing process. WAAM can be applied to cut manufacturing time, because structures created with WAAM still retain high strength, which is why titanium materials can be manufactured hollow to save money and time [20]. Titanium has several applications in the maritime industry, such as hull, piping and fastening parts, which receive high amounts of stress or heat during usage [21].

The last significant material used in the maritime industry is aluminium. Aluminium has several mechanical properties, such as great corrosion resistance and high strength to weight ratio. This in addition to the fact that aluminium is very common, light and affordable material makes it useful in the maritime industry. The downside of aluminium compared to the other materials is that aluminium has lower mechanical strength. Using WAAM to fabricate objects from aluminium is relatively quick and requires low energy input. However problems faced working with aluminium are residual stresses and the reactivity of aluminium [22]. Aluminium structures fabricated with

WAAM has opened many opportunities for the maritime industry. Due to WAAM's ability to create medium to large objects allows the creation of large ship parts. Many ships and boats are aluminium-based, and, for example, the structure of the ship's hull is usually bulbous to which WAAM is easily applied due to its ability to create complex objects. The future of aluminium in maritime industry lies with large superstructures [23].

2.3 Part manufacturing

2.3.1 Engine parts

Engine is one of the most mechanically complex parts of the ship due to the many moving parts, such as the crankshaft, pistons, turbocharger blades etc. These parts are in constant motion, and they need to withstand stresses due to the constant movement and high temperatures. The manufacturing of these parts requires flexibility and accuracy, whilst the parts need to maintain excellent mechanical properties and be economically viable. Wire-based AM methods can offer the required properties in addition to being profitable. [15]

A popular material used in engine part manufacturing is grey cast iron (GCI) and this is due to the combination of sufficient mechanical properties and wear resistance. However, with traditional manufacturing methods, such as casting and milling manufacturing large complex parts, such as engine blocks or crankshafts isn't economically beneficial, which is why engine blocks and crankshafts must be often repaired. However, repairing GCI with traditional methods creates large HAZ, which in turn decreases the overall strength of the material [18]. In figure 15 a crankshaft repaired using DED can be seen. For large parts manufacturing and repair with WAAM and DED-LB can be applied due to overcoming many of these shortcomings. Firstly, material choices can be changed, and many more alloys can be implemented to maintain mechanical properties, whilst additionally decreasing costs and weight by using different titanium and iron alloys. For the rotating parts, such as compressors and pistons require more than just strength, which is why superalloys, such as Inconel 718 can be used, which can improve the overall performance of the engine [17]. However, shortcoming with the manufacturing time and the lacklustre surface quality need to be accounted while designing the manufacturing processes, which is why size and weight optimization are crucial. Thus, careful planning of the process is integral, because making the parts light yet durable impacts the efficiency of the engine. The weight can be also affected by decreasing the thickness of the walls of different parts [24].

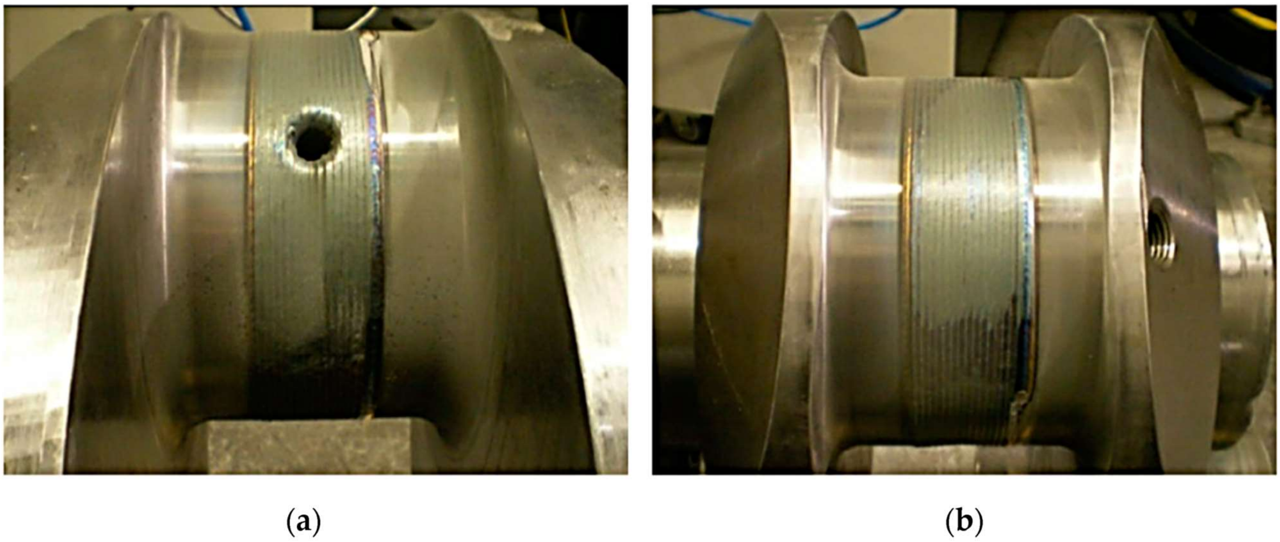

Figure 15 Crankshaft repaired with DED (a) before repair (b) after repair and post-processing [3]

In Figure 16 an engine bracket created by Wärtsilä, which used as little material as possible to optimize material usage and topology. The original bracket was made of an undisclosed metal, and weighed 31 kilograms, whereas the DED-fabricated engine bracket weighed only 21 kilograms. The process was done by using WAAM. [25]

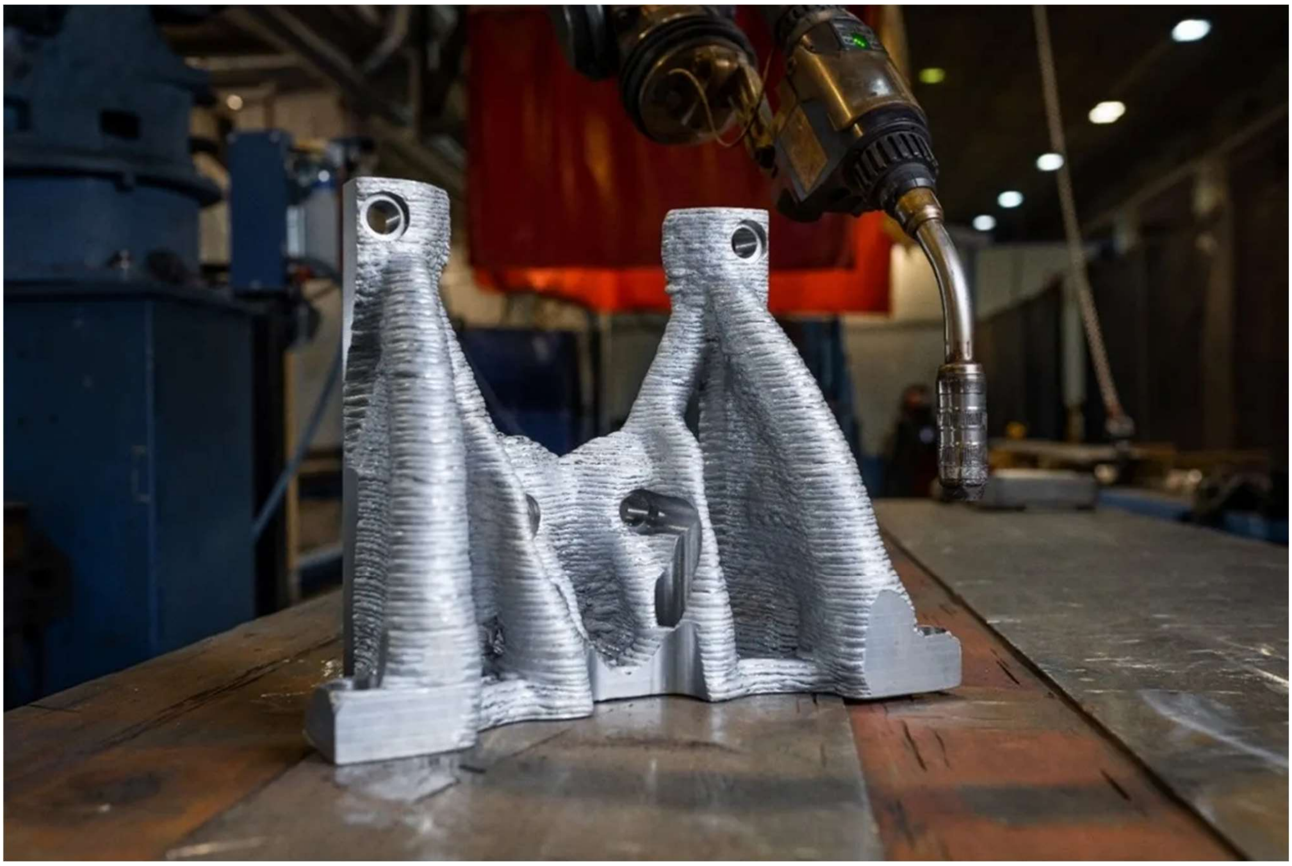

Figure 16 Wärtsilä engine bracket [25]

2.3.2 Hull parts

The design for the ship's hull is integral for the overall performance of the ship, because the shape and weight of the hull affect the ship's speed and manoeuvrability. Ship's hull also must fulfil safety requirements, which are tied to stability and the endurance of the hull. Other parts, such as compartments, bulb, panels, blocks and cost also need to be considered. Bulb is a relatively hard part to manufacture due to its size and it being double-curved, which means that the manufacturing of these parts is complex. The compartments and the structure of the bulb and hull can be seen in Figure 17. The manufacturing of the ship's hull and bulb is done by welding several curved metal blades together, but this process is time-consuming and dangerous, which is why the manufacturing and construction of the ship's hull requires an overhaul. [15]

Traditionally hull parts are created by hot rolling steel plates in order to curve them and cool them down quickly. This process has a negative effect on the strength, ductility and the surface quality of the material. However, this process isn't able to fabricate parts with complex structures, which means that there are obstacles regarding the size of these parts [26]. Implementation of new hull materials isn't easy due to the strict regulations and obstacles regarding the properties of the material, which are corrosion resistance, great mechanical properties and cost. The implementation of WAAM and DED-LB is thus an integral part for the manufacturing and construction of the hull and the bulb. The reduction of the hull's weight has been a sought-after improvement, yet it still needs to fulfil several regulations. For large ships these parts can be constructed from titanium or nickel alloys, because these materials are resistant to corrosive seawater, which makes them a noteworthy choice. With titanium the hull's walls can be constructed thinner, which reduces fuel consumption, material expenses and cuts manufacturing time. Nickel-based alloys can also be used for different piping solutions that are situated along the inside of the hull. For lighter vessels cheaper and lighter materials can be used, such as aluminium. The bulbous and double-curved parts and compartments can be fabricated with WAAM due to the flexibility of the WAAM process and the materials can also be joined together by using WAAM as a welding solution. The drawbacks of WAAM need to be taken also into account, because the parts need to be post-processed and because the strength requirements are strict, the small loss in strength needs to be accounted for. Overall integrating WAAM into this process cuts costs, manufacturing time, materials and manpower. [15]

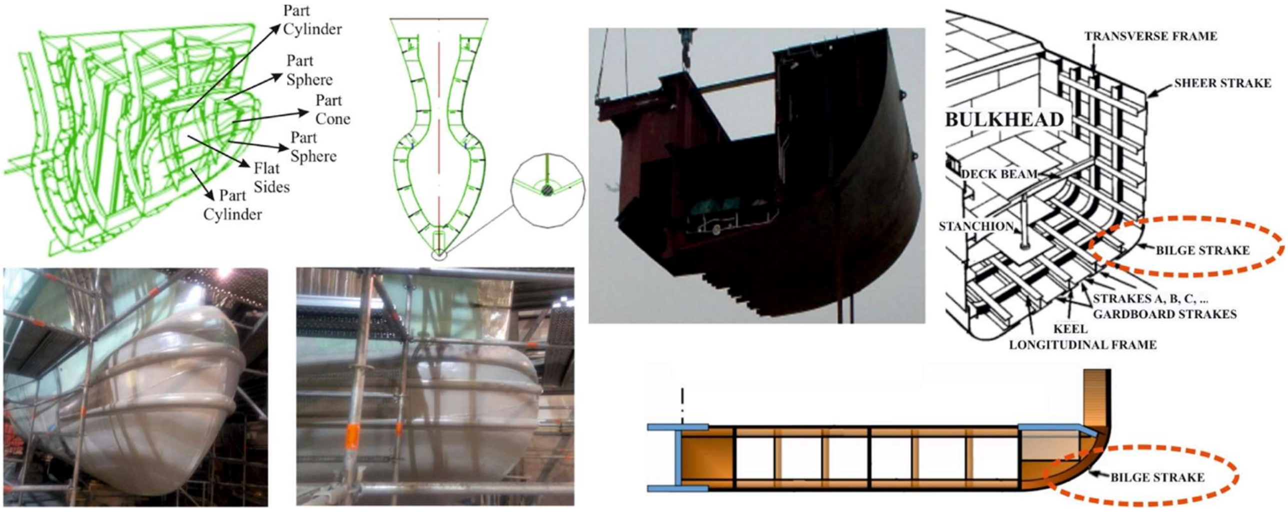

Figure 17 Ship's bulb and hull shape and compartments [15]

2.3.3 Steering components

Steering components, such as rudder and the propeller are cumbersome to manufacture. The manufacturing of these parts without automatization requires lots of manual labour and capital due to the long and energy-draining casting process, which also requires post-processing afterwards, which makes the traditional manufacturing processes ineffective in an on-demand economy. The casting process is usually sand casting, which wastes material relatively much, and the complex structure of propellers makes the process more complicated. Due to these downsides in the traditional manufacturing process, the implementation of AM methods is integral. The plethora of choices in wire diameter, wire material and great process parameters makes AM the future choice in steering component manufacturing. [15]

In Figure 18 the simple design of a ship's propeller is shown as can be seen from the expanded blade-part, the structure of a propeller is spiral-like with constant changes in the width of the blade. These difficult shapes can be relatively easily done with WAAM or DED-LB. Due to the multiaxial opportunities in WAAM and the possibility to implement rotating manufacturing tables, many dimensions can be reached that is very difficult or not possible using traditional methods. The speed of the process can also be improved by implementing multi-nozzle WAAM or DED-LB, which increases the overall deposition rate in the process. There is unfortunately waste in material and time in WAAM and DED-LB processes due to the need for support structures during the manufacturing process. However, material can also be saved during this process by the implementation of other materials as support structures. As mentioned before, propellers are most often manufactured from nickel-based alloys, such as bronze, NAB, Inconel or iron alloys. Manufacturing from stronger material, for example, titanium always brings extra material costs, however, this part can be avoided by making the propeller hollow. This saves material costs, time and fills the mechanical property requirements, such as stiffness. [15]

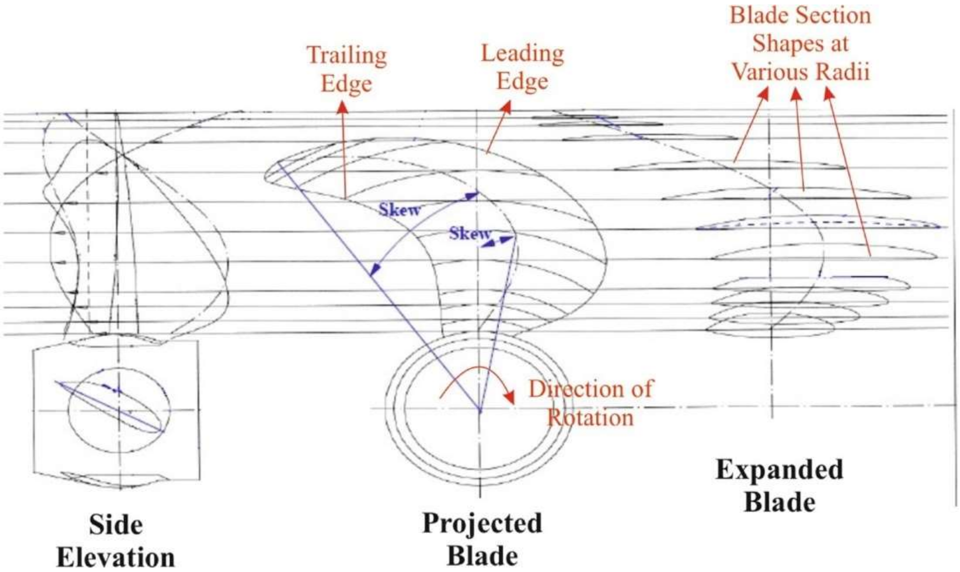

Figure 18 Shape and terminology of simple propeller [15]

The rudder is the most integral steering component, which imposes many requirements on the shape, size and type of the rudder. Great control needs to be maintained in difficult waterways, such as canals and the manoeuvrability of large ships is a necessity. Taşdemir et al (2021) describes the manufacturing of rudders as following: “Production of rudder is tedious since some plates must be formed, welded and provided with profiles.” The requirements for rudders are overall similar to propellers, because the manufacturing is cumbersome, structure is difficult, costs are large, and rudders weigh a lot. WAAM and DED-LB offer similar solution to the propeller with the creation of hollow rudders from strong materials, such as steel or titanium. The hollow rudders would have narrow supports beams inside the rudder, which saves space, manufacturing time and costs, while additionally maintaining the structure sturdy. An example of a hollow rudder can be seen in Figure 19. [15]

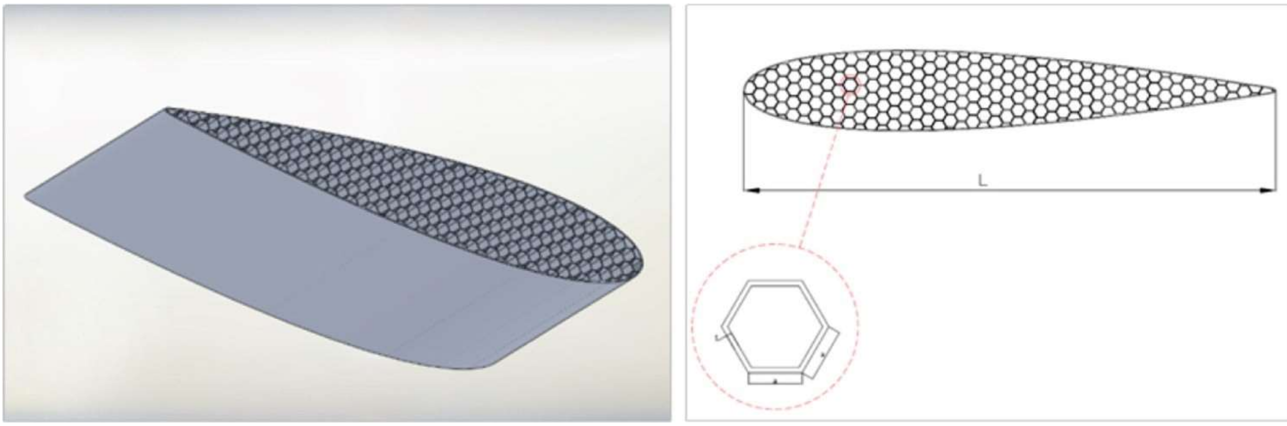

Figure 19 Cross-section of a rudder with “honeycomb” structure [15]

2.3.4 Case study: Propeller

With traditional manufacturing methods the construction of large parts is relatively slow and demand much manual labour, whereas AM opens the opportunity to manufacture parts using little manual labour with low material losses. In their study Ya et al (2018) examines the possibilities of creating cost-effective and on-demand spare parts in maritime industry, in this case a propeller. WAAM with MAG-type welding head and carbon dioxide as welding gas is used in this case and the welding wire is 1mm in diameter Lincoln Electric SG 2, which is coated with copper. The flexibility of WAAM manufacturing is also studied with different blade designs, which would be almost impossible to create using traditional manufacturing methods. Optimal welding conditions were ensured to create an optimal grain structure and reduce errors in surface quality. [27]

Four designs were made; first one was a single hollow blade half a meter in diameter. The hollow blade could enable cost-reduction and compensating the loss of mass with a sturdier material; however, the material needed to be corrosion-resistant due to the effects of saltwater on metal. The second design was a four-blade propeller with the use of blades from the first case. The third design was a solid three-blade propeller one meter in diameter. Designs 1 and 3 were post-processed using manual grinding tools, design 2 was milled, and the blade walls were uniform in thickness in these cases. The fourth design was similar to the third design with the implementation of varying wall thickness. All these finished designs or computer designs can be seen in Figure 20. [27]

The conclusions drawn from this study were that creating different WAAM-based propellers, whilst reducing costs is possible. Also, additional parts to the design, such as winglets at the tip of the blades or hollow blades, which are hard to manufacture with traditional methods can be more easily implemented with WAAM. Steps in propeller manufacturing, such as moulding and casting can be skipped with WAAM and the overall manufacturing time for the whole process can also be reduced.

Lastly, the manufacturing of propellers can be made more available, because manufacturing used to demand a lot of manual labour, machines and resources, whereas with WAAM the only required resources are the device itself with additional material and logistic costs. [27]

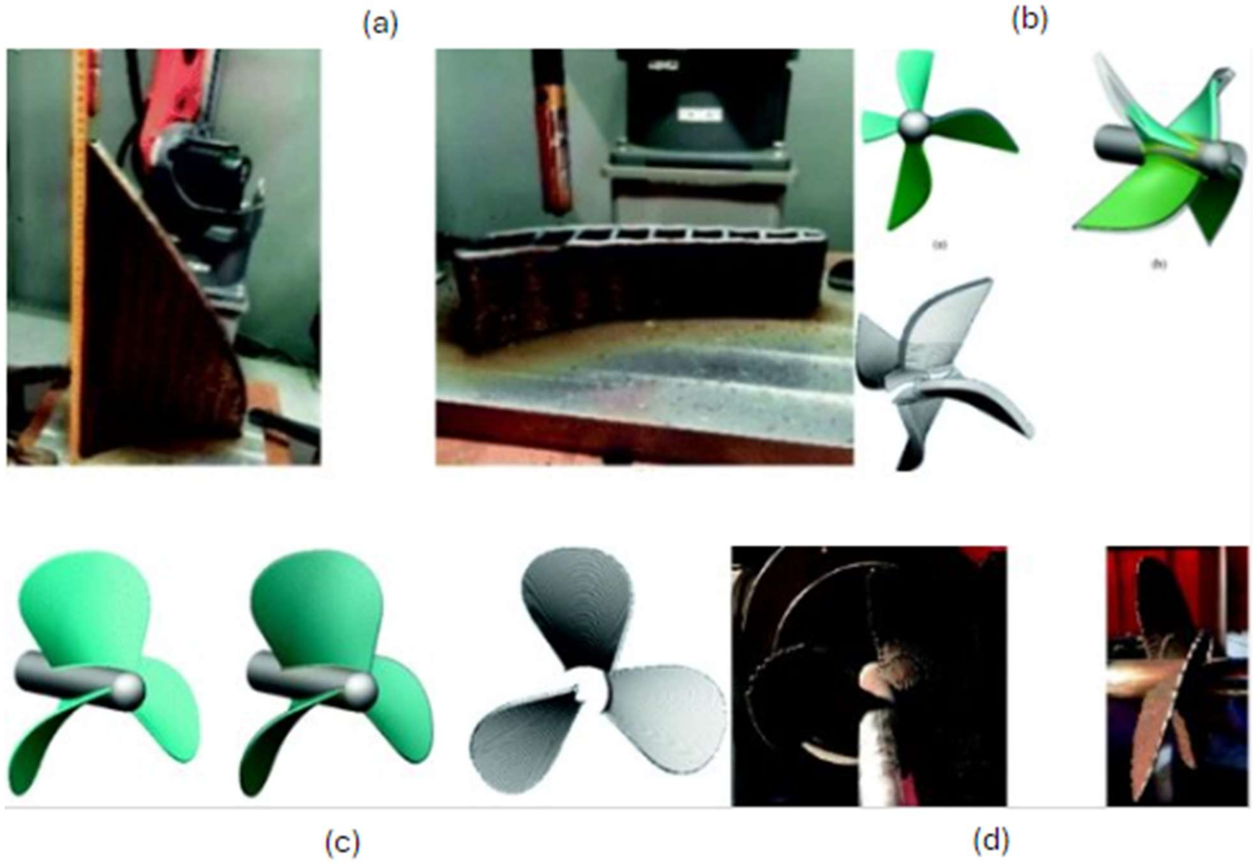

Figure 20 (a) Finished design 1 (b) Computer design for design 2 (c) Computer design for design 3 (d) Finished design 4 [27]

2.4 Repair

Due to the large costs of manufacturing medium to large ship parts, the repair of these parts is usually considered a viable option. The problem with repair is that the repaired spot has a greater chance of getting damaged due to the reduced mechanical properties. Additionally, the complexity of parts, such as the propeller blades brings challenges to the process. To preserve the mechanical properties and to ensure that the part has lower chance of breaking again, different steels can be used due to their high strength and resistance to seawater. Duplex stainless steel 2209 (DSS) is a promising material in the maritime industry due to high strength and corrosion resistance. However, DSS is prone to developing austenite in its microstructure, when exposed to high heat input. By using WAAM in repairing with DSS, the grain structure stays relatively uniform due to the low HAZ and therefore lower levels of austenite in the DSS. Low level of austenite is beneficial, because high levels of austenite would lower the material’s strength. Additionally, complex parts, such as chipped propeller blades can be fixed without needing to replace the whole propeller blade [28]. Engine parts are more complex and need to withstand more mechanical and thermal stresses, but they don’t require high corrosion resistance. In their study by Hamilton et al (2023) grey cast iron structure was repaired with stainless steel by using DED-LB. The results of this study were that the strength was retained, but the part experienced some residual stresses and elongation. However, these results are promising, because grey cast iron is perceived as a hard material to repair due to the high carbon content [18].

2.5 Quality improvement

Maritime industry has scrupulous demands for overall high quality due to the hazardous environment that ships operate and the high stresses that the ships are affected by. Due to this, parts created with AM need to achieve the same levels of hardness and resistance to strain, corrosion, heat, and fatiguing that are achieved by traditional manufacturing methods and in many cases overcome them. Shortcomings, such as surface quality, porosity, voids and cracks in material need to be detected and fixed in order to improve the reliability of AM processes. Quality improvements can be achieved with the help of machine learning and accurate process planning.

As mentioned before, products fabricated by WAAM mostly retain their mechanical properties, such as hardness and corrosion resistance. However, many problems come up by examining the microstructure of the material. These problems are hard to find by examining the material with the blind eye, so these problems require a monitoring system to detect these problems. Offline parameter optimization can be an answer to detect problems in structure during the fabrication process. The principles of offline parameter optimization are that constant data is collected during the process, which detects defects during the process and fixes them by, for example, adding more feedstock material to a layer if necessary. To achieve successful offline parameter optimization, several simulations must be done by examining the effects of different parameters during the manufacturing process, such as feed rate, speed etc. These machine learning implementations could improve the overall quality of the manufactured product in the long run, but the sensors and equipment required presents extra costs to the process. In Figure 21 a structure fabricated by WAAM and later fixed by applying machine learning to the process and a setup for the weld pool sensing system can be seen. [29]

Quality improvements can also be achieved by constantly monitoring the heat added into the process, because during the process equipment might face some overheating, which in turn affects the quality of the fabricated structure. Heat expansion, similar to the problems discussed in the previous paragraph can be mitigated by applying sensors and data gathering to the process. This process would require two heat sensors, one at the beginning of each layer and one in the middle of each layer. Both sensors would compare heat data to the previous layers and from this predict the temperature of the next layer. This would control the heat added to the process and in turn mitigate heat expansion and residual stresses. [30]

Figure 21 (a) Standard tool path (b) fixed tool path. Right side a 3D weld pool sensing system setup [29]

2.6 Safety, reliability and endurance

DED processes have many safety advantages regarding the manufacturing process itself and the structural integrity of the manufactured parts. Compared to the traditional manufacturing methods, WAAM and DED-LB are considered safer than the traditional methods due to the manufacturing being automated and monitored by only a handful of personnel. Also, the lower heat input makes the working environment much safer and unlike powder-based AM, wire-based AM doesn't cast powder into the air, which is harmful to health. However, due to the safety demands, more emphasis is placed on the reliability and endurance of parts fabricated by wire DED. The parts need to endure high mechanical stresses, heat and corrosive sea water, thus manufacturing enduring structures with high strength and low fatiguing is crucial. [31]

Many structural shortcomings can be studied due to the ease of manufacturing prototypes quickly with wire DED, especially WAAM. Shortcomings, such as residual stresses can be controlled by optimizing the heat input or incorporating smart systems into the process that analyse data and change parameters during the manufacturing process. This creates a safety net, the goal of which is to prevent structural collapse before the part is in usage. Additionally, the parts can be made lighter and simpler due to the freer build dimensions, which makes the parts safer to transport and work with. Repair can be done on complex parts with little losses to mechanical properties, such as propeller blades, which additionally reduces costs. [31]

Wire-based DED can overall be deemed as a safe manufacturing method, which can create parts with similar mechanical properties compared to existing manufacturing methods much cheaper and faster without significant structural drawbacks. However, the processes require optimization and testing in order to mitigate the drawbacks of this process. The many benefits of AM in maritime industry can be seen in Figure 22. [31]

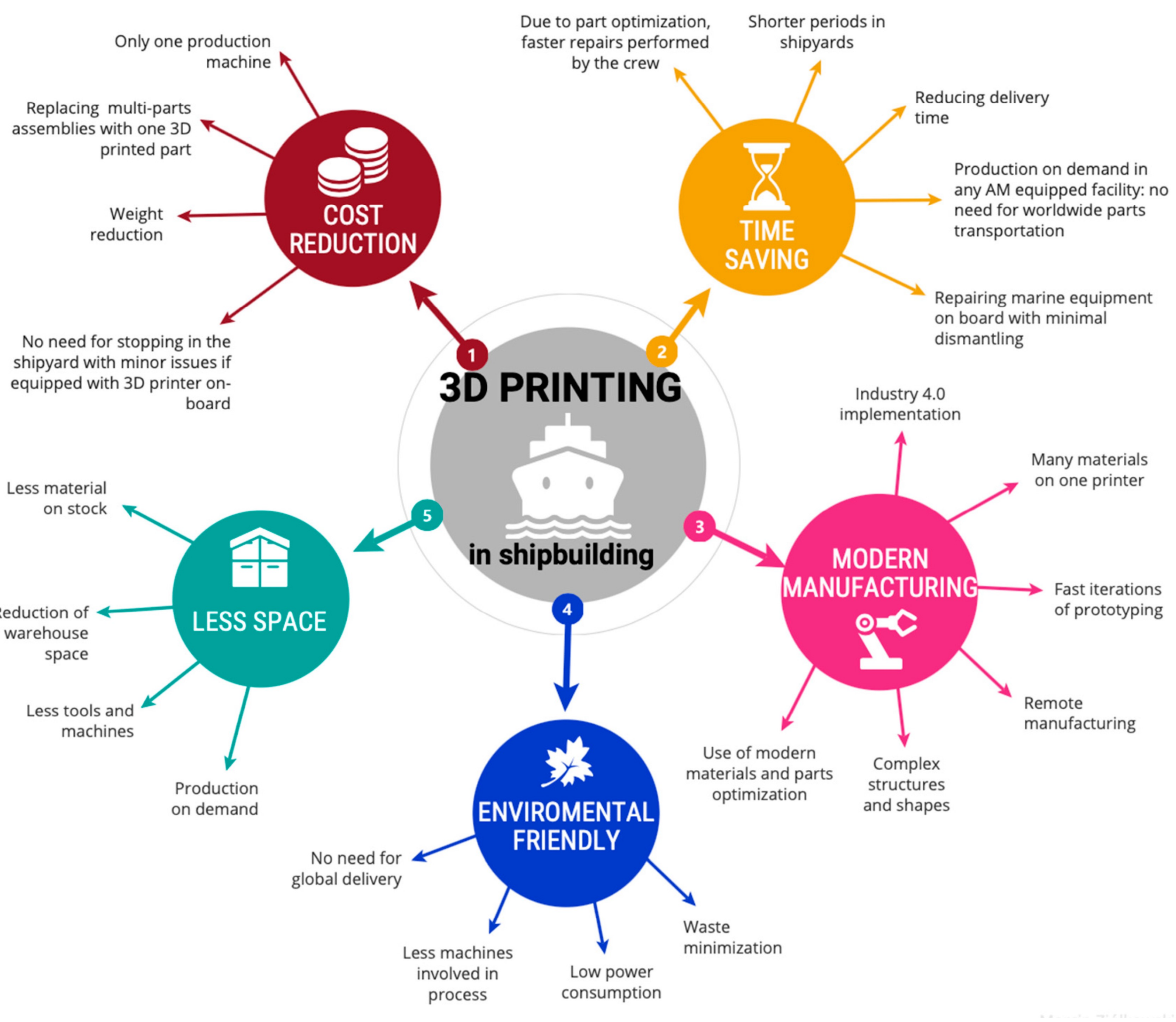

Figure 22 Benefits of AM in maritime industry [31]

3. Conclusions

Wire-based DED is an emerging manufacturing, which can be applied to several fields. The need for different wire-based DED methods can be chosen by manufactured structure's requirements, for example, size and surface quality. For medium- to large-sized structures with high manufacturing speed WAAM is the manufacturing choice, but the high manufacturing speed comes in return for poorer surface quality. DED-LB can create structures with superior surface quality, but with slower manufacturing speed. Structures from different materials created by wire-based DED mostly retain their attributes, such as resistance to corrosion and heat with small penalty to some mechanical properties, such as strength. However, the loss in strength can be mitigated by reinforcing materials with other alloys or optimizing the process parameters. Additionally, there are small changes to the grain structure, for example, in iron-based alloys miscellaneous amount of austenite can be found after a DED process. Additionally, residual stresses created by the heating and cooling cycles can be mitigated by optimizing heat input and process parameters. Moreover, process parameter optimization can be implemented by manufacturing several prototypes or by implementing machine learning into the process.

Wire-based DED can be introduced to the maritime industry to create parts and structures with complex dimensions and high mechanical property demands. Parts that were previously created with moulding, such as propellers, rudders and engine components can be created more easier by using wire-based DED. This would cut costs due to the high material efficiency, lower heat input and less personnel needed to partake in the process. New structural designs, which couldn't be manufactured with traditional methods can be created with wire-based DED, such as hollow rudders and propellers. The losses to strength from the hollow structure can be compensated by changing the material from bronze to titanium or no material change is needed by adding small supporting structures inside of the structure from the original material or from other stronger material. Manufacturing and assembly of large bow and bulb parts can be implemented, which would save time and decrease the need for additional welding.

Wire-based DED can also be applied to repair components with complex structures instead of replacing them. Chipped propeller blades can be fixed by filling the chipped part with feedstock material and postprocessing the added material, without significant losses to the mechanical properties of the blade. Conclusively, wire-based DED offers a cheaper and faster alternative to traditional manufacturing methods with high mechanical properties whilst maintaining great accuracy and flexibility. Applying these manufacturing methods is the future of maritime industry and shipbuilding.

4. References

[1] L. Gardner, ‘Metal additive manufacturing in structural engineering – review, advances, opportunities and outlook’, *Structures*, vol. 47, pp. 2178–2193, Jan. 2023, doi: 10.1016/j.istruc.2022.12.039.

[2] D. Svetlizky *et al.*, ‘Laser-based directed energy deposition (DED-LB) of advanced materials’, *Materials Science and Engineering: A*, vol. 840, p. 142967, Apr. 2022, doi: 10.1016/j.msea.2022.142967.

[3] A. Saboori, A. Aversa, G. Marchese, S. Biamino, M. Lombardi, and P. Fino, ‘Application of Directed Energy Deposition-Based Additive Manufacturing in Repair’, *Applied Sciences*, vol. 9, no. 16, p. 3316, Aug. 2019, doi: 10.3390/app9163316.

[4] Z. Li *et al.*, ‘High deposition rate powder- and wire-based laser directed energy deposition of metallic materials: A review’, *International Journal of Machine Tools and Manufacture*, vol. 181, p. 103942, Oct. 2022, doi: 10.1016/j.ijmachtools.2022.103942.

[5] S. Nowotny, S. Thieme, D. Albert, F. Kubisch, R. Kager, and C. Leyens, ‘Generative Manufacturing and Repair of Metal Parts through Direct Laser Deposition Using Wire Material’, in *Digital Product and Process Development Systems*, G. L. Kovács and D. Kochan, Eds., Berlin, Heidelberg: Springer, 2013, pp. 185–189. doi: 10.1007/978-3-642-41329-2_20.

[6] C. Buchanan and L. Gardner, ‘Metal 3D printing in construction: A review of methods, research, applications, opportunities and challenges’, *Engineering Structures*, vol. 180, pp. 332–348, Feb. 2019, doi: 10.1016/j.engstruct.2018.11.045.

[7] J. D. Hamilton, D. Trauernicht, D. Cormier, and I. V. Rivero, ‘Laser-Based Directed Energy Deposition Remanufacturing of Gray Cast Iron using Stainless Steel 316L and Inconel 625 Filler Materials’, *Advanced Engineering Materials*, vol. 25, no. 24, p. 2301212, 2023, doi: 10.1002/adem.202301212.

[8] R. Rumman, D. A. Lewis, J. Y. Hascoet, and J. S. Quinton, ‘Laser Metal Deposition and Wire Arc Additive Manufacturing of Materials: An Overview’, *Archives of Metallurgy and Materials*, pp. 467–473, Mar. 2019, doi: 10.24425/amm.2019.127561.

[9] L. Squires, E. Roberts, and A. Bandyopadhyay, ‘Radial bimetallic structures via wire arc directed energy deposition-based additive manufacturing’, *Nat Commun*, vol. 14, no. 1, Art. no. 1, Jun. 2023, doi: 10.1038/s41467-023-39230-w.

[10] E. Karayel and Y. Bozkurt, ‘Additive manufacturing method and different welding applications’, *Journal of Materials Research and Technology*, vol. 9, no. 5, pp. 11424–11438, Sep. 2020, doi: 10.1016/j.jmrt.2020.08.039.

[11] K. Li *et al.*, ‘Additive manufacturing of ultra-high strength steels: A review’, *Journal of Alloys and Compounds*, vol. 965, p. 171390, Nov. 2023, doi: 10.1016/j.jallcom.2023.171390.

[12] D.-H. Ding, Z.-X. Pan, C. Dominic, and H.-J. Li, ‘Process Planning Strategy for Wire and Arc Additive Manufacturing’, in *Robotic Welding, Intelligence and Automation*, T.-J. Tarn, S.-B. Chen, and X.-Q. Chen, Eds., in Advances in Intelligent Systems and Computing. Cham: Springer International Publishing, 2015, pp. 437–450. doi: 10.1007/978-3-319-18997-0_37.

[13] D. Svetlizky *et al.*, ‘Directed energy deposition (DED) additive manufacturing: Physical characteristics, defects, challenges and applications’, *Materials Today*, vol. 49, pp. 271–295, Oct. 2021, doi: 10.1016/j.mattod.2021.03.020.

[14] ‘The Pressure Vessel 3D Printed by ANDRITZ Savonlinna Works Oy and FAME Ecosystem Is a European Giant – Fame3D’. Accessed: Mar. 13, 2024. [Online]. Available: https://fame3d.fi/the-pressure-vessel-3d-printed-by-andritz-savonlinna-works-oy-and-fame-ecosystem-is-a-giant/

[15] A. Taşdemir and S. Nohut, ‘An overview of wire arc additive manufacturing (WAAM) in shipbuilding industry’, *Ships and Offshore Structures*, vol. 16, no. 7, pp. 797–814, Aug. 2021, doi: 10.1080/17445302.2020.1786232.

[16] C. Shen *et al.*, 'The influence of post-production heat treatment on the multi-directional properties of nickel-aluminum bronze alloy fabricated using wire-arc additive manufacturing process', *Additive Manufacturing*, vol. 23, pp. 411–421, Oct. 2018, doi: 10.1016/j.addma.2018.08.008.
[17] C. Li, R. Karimbaev, S. Wang, A. Amanov, D. Wang, and M. Abdel Wahab, 'Fretting wear behavior of Inconel 718 alloy manufactured by DED and treated by UNSM', *Sci Rep*, vol. 13, no. 1, Art. no. 1, Jan. 2023, doi: 10.1038/s41598-023-28128-8.
[18] J. D. Hamilton, S. Sorondo, B. Li, H. Qin, and I. V. Rivero, 'Mechanical behavior of bimetallic stainless steel and gray cast iron repairs via directed energy deposition additive manufacturing', *Journal of Manufacturing Processes*, vol. 85, pp. 1197–1207, Jan. 2023, doi: 10.1016/j.jmapro.2022.12.029.
[19] W. Jin, C. Zhang, S. Jin, Y. Tian, D. Wellmann, and W. Liu, 'Wire Arc Additive Manufacturing of Stainless Steels: A Review', *Applied Sciences*, vol. 10, no. 5, Art. no. 5, Jan. 2020, doi: 10.3390/app10051563.
[20] Z. Lin, K. Song, and X. Yu, 'A review on wire and arc additive manufacturing of titanium alloy', *Journal of Manufacturing Processes*, vol. 70, pp. 24–45, Oct. 2021, doi: 10.1016/j.jmapro.2021.08.018.
[21] I. V. Gorynin, 'Titanium alloys for marine application', *Materials Science and Engineering: A*, vol. 263, no. 2, pp. 112–116, May 1999, doi: 10.1016/S0921-5093(98)01180-0.
[22] B. Tomar, S. Shiva, and T. Nath, 'A review on wire arc additive manufacturing: Processing parameters, defects, quality improvement and recent advances', *Materials Today Communications*, vol. 31, p. 103739, Jun. 2022, doi: 10.1016/j.mtcomm.2022.103739.
[23] O. F. Hosseinabadi and M. R. Khedmati, 'A review on ultimate strength of aluminium structural elements and systems for marine applications', *Ocean Engineering*, vol. 232, p. 109153, Jul. 2021, doi: 10.1016/j.oceaneng.2021.109153.
[24] J. Gray and C. Depcik, 'Review of Additive Manufacturing for Internal Combustion Engine Components', *SAE International Journal of Engines*, vol. 13, no. 5, pp. 617–632, 2020.
[25] 'How to print with metal – on a big scale', Etteplan. Accessed: Mar. 04, 2024. [Online]. Available: https://www.etteplan.com/about-us/insights/how-print-metal-big-scale/
[26] A. Vahedi Nemani, M. Ghaffari, and A. Nasiri, 'Comparison of microstructural characteristics and mechanical properties of shipbuilding steel plates fabricated by conventional rolling versus wire arc additive manufacturing', *Additive Manufacturing*, vol. 32, p. 101086, Mar. 2020, doi: 10.1016/j.addma.2020.101086.
[27] W. Ya and K. Hamilton, 'On-Demand Spare Parts for the Marine Industry with Directed Energy Deposition: Propeller Use Case', in *Industrializing Additive Manufacturing - Proceedings of Additive Manufacturing in Products and Applications - AMPA2017*, M. Meboldt and C. Klahn, Eds., Cham: Springer International Publishing, 2018, pp. 70–81. doi: 10.1007/978-3-319-66866-6_7.
[28] K. Wu *et al.*, 'Effect of variable polarity during cold metal transfer on microstructure and mechanical properties of directed energy deposition-arc built 2209 duplex stainless steel', *Additive Manufacturing*, vol. 75, p. 103750, Aug. 2023, doi: 10.1016/j.addma.2023.103750.
[29] F. He *et al.*, 'Research and application of artificial intelligence techniques for wire arc additive manufacturing: a state-of-the-art review', *Robotics and Computer-Integrated Manufacturing*, vol. 82, p. 102525, Aug. 2023, doi: 10.1016/j.rcim.2023.102525.
[30] Y. Zhao, Y. Jia, S. Chen, J. Shi, and F. Li, 'Process planning strategy for wire-arc additive manufacturing: Thermal behavior considerations', *Additive Manufacturing*, vol. 32, p. 100935, Mar. 2020, doi: 10.1016/j.addma.2019.100935.
[31] M. Ziółkowski and T. Dyl, 'Possible Applications of Additive Manufacturing Technologies in Shipbuilding: A Review', *Machines*, vol. 8, no. 4, Art. no. 4, Dec. 2020, doi: 10.3390/machines8040084.