Tampere University

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# COLD SPRAY COATING AND REPAIR OF PROPELLERS

## Surface Treatment, Overhaul and Repair

Faculty of Engineering and Natural Sciences
Master of Science Thesis
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# ABSTRACT

Henri Moilanen: Cold spray coating and repair of propellers: surface treatment, overhaul, and repair
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The thesis work studies the use of cold spray thermal spray method for coating and repairing marine propellers. The main areas of interest are protecting the propeller from corrosion by utilizing a cold sprayed barrier coating and the repair of cavitation damage on the propeller blade using cold spray. The use of cold spray is evaluated by a literature review on the coating materials, by analysing the cost of cold sprayed coatings and by comparing cold spray to alternative methods.

Theory part of the thesis discusses propellers, materials used for propeller manufacturing and the cold spray method. Main types of propellers, propeller repair and maintenance procedures and a typical propeller manufacturing process are discussed in Chapter 2. Operating conditions affecting propeller design and material selection such as corrosion, cavitation and impact loading and biological fouling are discussed in Chapter 3. Currently used propeller materials, possible alternative propeller materials and interesting coating and repair materials are discussed in Chapter 4. Chapter 5 discusses the operating principle of cold spray method, commercially available cold spray equipment, the spraying process from manufacturing standpoint and the economics of cold spray.

The case study on the propeller coating and repair is discussed in Chapter 6. The case study consists of analysing propeller coating costs, predicting the financial saving potential and net present value of the propeller as a function of propeller size by using a MATLAB script. The feasibility of using cold spray for propeller repair is also discussed based on a qualitative comparison of the cold spray method against the alternative repair methods.

Last chapters discuss the uncertainties and risks associated with coated propellers and cold sprayed repairs as well as future research topics.

Keywords: propeller, cold spray, thermal spray, corrosion, coating

# TIIVISTELMÄ

Henri Moilanen: Potkurien pinnoittaminen ja korjaaminen kylmäruiskutusmenetelmän avulla
Diplomityö
Tampereen Yliopisto
Konetekniikan DI-tutkinto-ohjelma
Syyskuu 2020

Diplomityössä tutkitaan kylmäruiskutusmenetelmän käyttömahdollisuuksia potkureiden pinnoittamisessa ja korjauksessa. Tärkeimmät tutkimuskohteet ovat potkurin korroosiosuojapinnoittaminen sekä kavitaatiovaurioiden korjaus. Työssä tutkimuskysymyksiin vastataan vertailemalla pinnoitemateriaalien ominaisuuksia aiempiin tutkimuksiin pohjaten, analysoimalla pinnoittamisen kustannuksia sekä vertailemalla kylmäruiskutusmenetelmää nykyisin käytettyihin ratkaisuihin.

Työn teoriaosuudessa tutustutaan potkureihin, potkurimateriaaleihin sekä kylmäruiskutusmenetelmään. Potkureista esitellään yleisimmin käytetyt potkurityypit, potkureiden korjaus- ja kunnossapitomenetelmiä, sekä tyypillisen potkurivalmistusprosessin vaiheet. Potkurimateriaaleihin liittyen työssä käsitellään materiaalivalintaan vaikuttavia tekijöitä kuten korroosiota, kavitaatiota, eroosiota ja iskukuormitusta, sekä kasvuston kertymistä. Työssä tutustutaan myös yleisimmin käytettyihin potkurimateriaaleihin ja niiden ominaisuuksiin sekä mahdollisiin vaihtoehtoisiin potkurimateriaaleihin ja niiden valintaperusteisiin. Kylmäruiskutusmenetelmästä esitetään menetelmän toimintaperiaate, kaupallisesti saatavia kylmäruiskutusjärjestelmiä sekä pinnoittamiseen liittyvät työvaiheet.

Kylmäruiskutusmenetelmän käyttöä potkureiden pinnoituksessa ja korjauksessa arvioidaan materiaaliominaisuuksien, kustannusanalyysin sekä kvalitatiivisen tarkastelun kautta. Eri pinnoitemateriaalien käyttökelpoisuutta arvioidaan aiempien tutkimusten kautta, huomioiden eri materiaalien ruiskutettavuuden, pinnoitteen laadun ja mekaaniset ominaisuudet sekä yleisen soveltuvuuden esitettyihin käyttökohteisiin. Kustannusanalyysillä arvioidaan MATLAB skriptin avulla potkurin pinnoittamisen kustannuksia ja kustannukseen vaikuttavia tekijöitä potkurin koon mukaan. Pinnoitteen käytön potentiaalisia rahallisia hyötyjä pyritään arvioimaan ennustamalla aluksen polttoainekustannuksia aluksen käyttöprofiilin ja moottoritehon perusteella. Kylmäruiskutusmenetelmän käyttöä potkurin vaurioiden korjaamiseen arvioidaan vertailemalla sen ominaisuuksia vaihtoehtoisiin korjausmenetelmiin.

Työn tulosten perusteella pyritään arvioimaan kylmäruiskutusmenetelmän käytön kannattavuutta sekä menetelmän käyttöön liittyviä riskejä sekä pinnoitus että korjauskäytössä. Työn viimeisessä kappaleessa esitetään tuntemattomiin tekijöihin pohjaten jatkotutkimuskohteita.

Avainsanat: potkuri, kylmäruiskutus, terminen pinnoittaminen, korroosio, pinnoite

Tämän julkaisun alkuperäisyys on tarkastettu Turnitin OriginalityCheck -ohjelmalla.

# PREFACE

This thesis work anticipates the final leg of my engineering studies at Tampere University, a journey which has been demanding at times, but will surely be fondly remembered. The presented work has broadened my knowledge in engineering sciences while also reminding that there is still much to learn and develop.

For this experience I would like to express my gratitude towards Kongsberg Maritime Finland Oy and especially Joni Keski-Rahkonen and Pasi Villanen for enabling this venture to study previously unknown subject, examiners Petri Vuoristo and Eric Coatanea who have given guidance and valuable feedback during the writing process and to my peers which have given me both support and pressure to finish my studies in a timely manner.

Tampere, 27.09.2020

Henri Moilanen

# TABLE OF CONTENT

# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| BSFC | Brake specific fuel consumption |
| $C$ | Constant which reflects average power values for certain propeller type |
| CFD | Computer fluid dynamics |
| $D_{prop}$ | Propeller diameter |
| FPWJ | Forced pulsed water jet |
| HPCS | High pressure cold spray |
| HSFO | High sulphur fuel oil |
| HVOF | High velocity oxygen fuel |
| LPCS | Low pressure cold spray |
| NAB | Nickel aluminium bronze |
| $n_M$ | Propeller rotations per minute |
| $P_M$ | Absorbed propeller power |
| SLD | Supersonic laser deposition |
| VLSFO | Very low sulphur fuel oil |
| $V_{tip}$ | Velocity at the propeller blade tip |

# 1. INTRODUCTION

Marine propellers operate in a hostile environment where the propeller and its material are subjected to erosion, corrosion, biological fouling, and impact loading. This environment both severely restricts the available materials for propeller fabrication and causes damages to the existing propellers, which necessitates their repair. If corrosion of propellers could be mitigated by using a corrosion resistant coating, they could be manufactured from a more cost-effective material. Alternatively, stronger propeller material would allow hydrodynamically more efficient propellers to be manufactured, which would reduce the cost and environmental impact of operating the vessel.

Cold spray is a relatively new thermal spray process which can produce dense and oxide free deposits from many metallic materials. In many fields cold spray shows promise for use in corrosion protection and repair applications. This study evaluates the use of cold spray for repair and coating of marine propellers based on experiences found in literature, financial analysis and by qualitive comparison against competing coating and repair methods.

Theory part of the thesis discusses propellers and their operating conditions, materials, and cold spray process. Main propeller types, propeller manufacturing and maintenance are discussed in Chapter 2. Chapter 3 introduces the main environmental factors that affect the propeller design and material selection. Chapter 4 discusses the currently used materials for propeller fabrication, alternative propeller materials and possible coating materials. The coating materials are discussed based on a literature review, which focuses on the properties of cold sprayed materials. Chapter 5 discusses the operating principle of cold spray, commercially available spray systems, thermal spray as part of manufacturing process and the cost estimation of a cold spray process using a MATLAB script.

Chapter 6 evaluates the use of cold spray for coating and repair of propeller based on a financial and qualitative analysis. Conclusion of this study, recommendations, and future research paths are discussed in the final chapters.

# 2. PROPELLER

Propellers used in marine applications can be divided to two subcategories: fixed pitch and controllable pitch propellers. Fixed pitch propellers consist of either a single piece propeller or of a separate propeller hub and blades that are fixed to the hub (Kongsberg Maritime, 2020). Controllable pitch propellers feature a hub and separate blades whose pitch can be adjusted to vary the loading of the propeller and change the direction of the thrust as needed (Kongsberg Maritime, 2020; Carlton, 2012). Illustration of fixed pitch and controllable pitch propellers is presented in Figure 1.

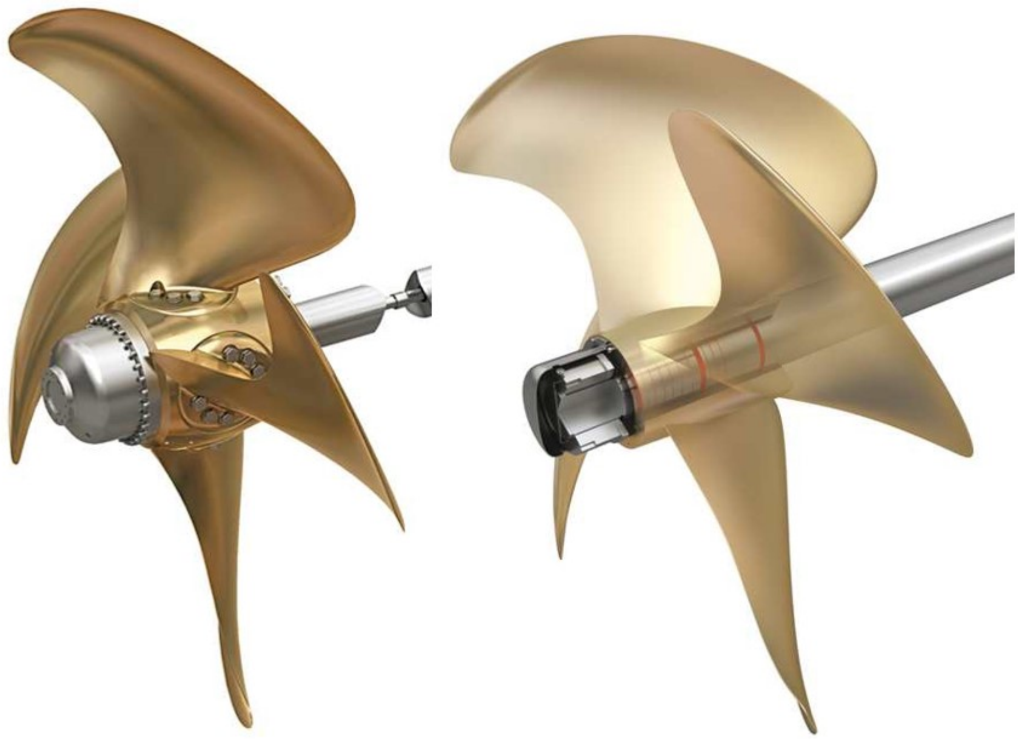

***Figure 1. Changing pitch and fixed pitch monobloc propeller. (Kongsberg Maritime, 2020)***

Fixed pitch propellers are the most used propeller type with Carlton, noting that their market share was around 65 percent in 2012 of all propellers. Changing pitch propellers have been gradually gaining popularity and as of 2012 they accounted for approximately 35 percent of propeller market. Changing pitch propellers are typically used in applications which require better manoeuvrability and more precise control of thrust. Examples of such applications are tugboats, vessels with dynamic position capability and ferries operating on short routes, which are often berthed. (Carlton, 2012, p. 19)

Propellers can be manufactured from many different materials based on their use case, with nickel aluminium bronze being the most popular material for general purpose propellers. Stainless steel alloys are commonly used in applications, where better mechanical properties are required over cost and corrosion properties. Propellers used in arctic conditions and most prominently ice breakers are made from martensitic stainless-steels and feature more conservative geometry to handle the additional loading caused by ice to propeller interaction. Traditionally arctic shipping has been restricted to arctic area supply and ice breaking operations, where efficiency and noise have been a lesser concern when compared to open water shipping. However, in recent years the growing interest on merchant shipping in arctic waters has created the need for propellers that are efficient in open water conditions while being capable of operating in arctic conditions. (Pustoshny, et al., 2017; Scröder, et al., 2017)

## 2.1 Propeller manufacturing

This chapter describes the basic manufacturing process for a fixed pitch marine propeller. Marine propellers are practically always designed and manufactured for a specific vessel, where the propeller design is optimized based on the vessel's powerline, operating profile and hull shape. The structural design and material selection of the propeller are based on rules dictated by the governing classification society, while the propeller design is optimized by using both computer fluid dynamics (CFD) software and experimental methods such as cavitation tunnels. (DNV-GL, 2015, p. 432; Carlton, 2012)

Propellers are traditionally manufactured by sand casting as it is the most cost-effective way of manufacturing large parts in small volumes (Carlton, 2012, p. 418). The manufacturing process begins by fabricating the pattern which is used to make the mould for the casting. The pattern is manufactured from materials such as expanded polystyrene foam and wood by using a CNC router to shape the material. For large propellers, the pattern usually includes the shape of single propeller blade and hub. The pattern is then rotated to form the impression of each blades while making the mould. Typical propeller pattern is presented in Figure 2. (Carlton, 2012, p. 417; Wärtsilä, 2016)

*Figure 2. Pattern used for making casting mold. (Wärtsilä, 2016)*

The mould for sand casting is produced in two halves which represent the pressure and suction sides of the propeller. Typical mould arrangement and runner system are presented in Figure 3.

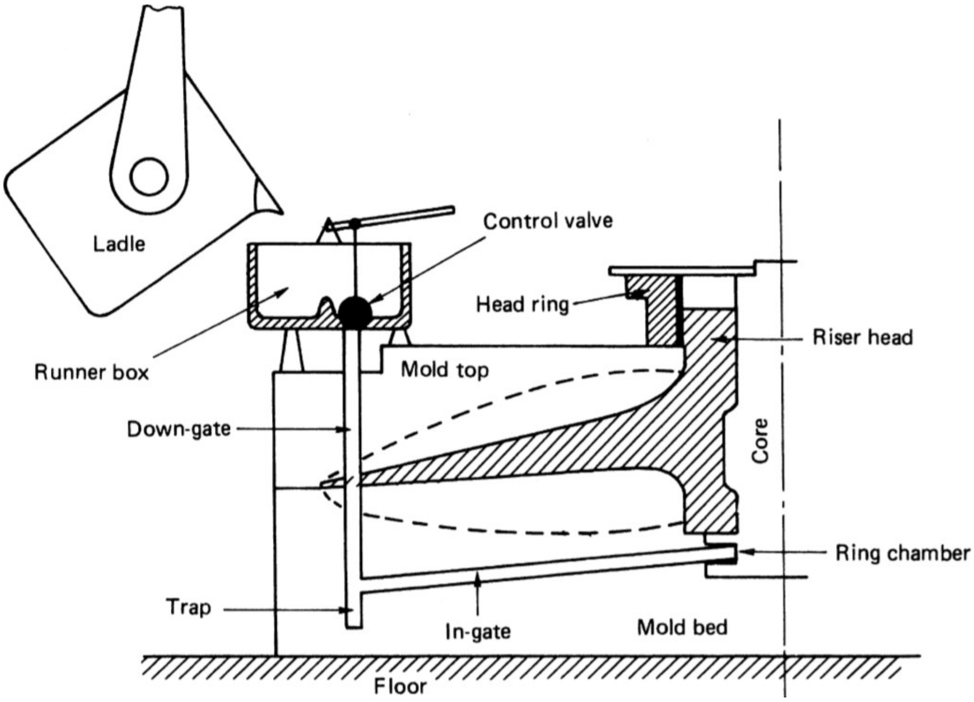


*Figure 3. Typical mold arrangement and runner system. (Carlton, 2012, p. 418)*

The runner system in the mould is designed in such a way that the material flow rate is maximized while maintaining low turbulence within the flow. Minimizing turbulence is important as turbulence can cause oxides to be trapped inside the casting, which can compromise the structural integrity of the part. After the casting, the part is left to cool for a few days depending on the size of the part. Classification societies can require test specimens to be cast on various parts of the propeller casting. Mechanical tests are conducted for the specimen to determine the material properties of the casting. (Germanischer Lloyd Aktiengesellschaft, 2019)

After the part has cooled the mould is destroyed to reveal the casting. The part is then fettled to remove all unnecessary material such as risers, flash, and venting systems. After fettling, the propeller shaft bore is machined using a vertical lathe. Subsequently the blades are cut to their correct profile by a CNC milling machine. The machining stage is presented in Figure 4. (Carlton, 2012, p. 419; Wärtsilä, 2016)

***Figure 4. Propeller blade machining. (Yuanhang propellers manufacturing Co Ltd, 2020)***

After the machining, the propeller is inspected for casting defects. Classification societies have rules regarding where and how large defects of different types can be at different areas of the propeller. Found defects are documented and reported to the classification society. The defects are then repaired either by adding or removing material as required. (Germanischer Lloyd Aktiengesellschaft, 2019) Ultrasonic testing of a propeller blade is presented in Figure 5.

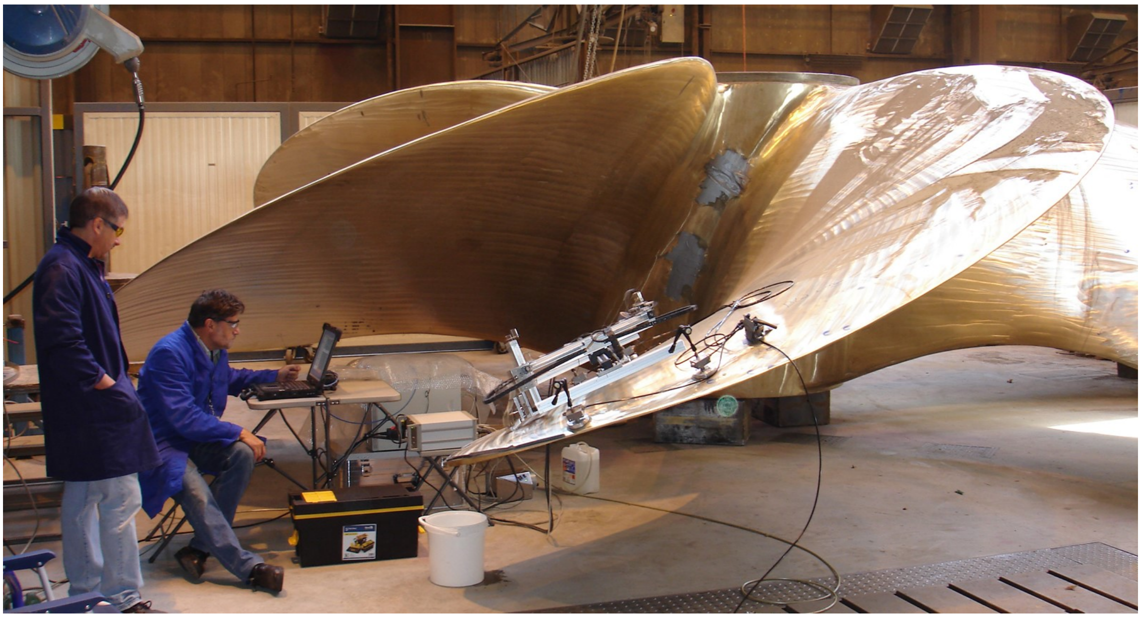

***Figure 5. Ultrasonic testing of a propeller. (Fraunhofer-Gesellschaft, 2012)***

Finally, the propeller is polished, balanced and marked before shipping it to a customer. It is worth noting that while extra polishing increases the efficiency of the propeller, polishing to fine grit is not beneficial as biological fouling will quickly increase the effective surface roughness of the propeller. (Germanischer Lloyd Aktiengesellschaft, 2019, p. 419; Wärtsilä, 2016; Carlton, 2012)

## 2.2 Propeller modification, repair, and maintenance

Propellers operate in a hostile environment which can damage the propeller through corrosion, cavitation, fouling, and by mechanical loading. Additionally, propeller modification may be necessary if the operating profile of the vessel is altered or the propeller proves to be wrongly dimensioned. This chapter presents some of the ways how propellers are modified, maintained, and repaired.

Propeller polishing is a routine maintenance operation which aims to minimize propeller surface roughness by removing fouling and smoothing the surface by grinding. The operation consists of removal of fouling and scaling layer from the propeller using a coarse abrasive sanding pad. The resulting clean surface is then further polished to finer surface roughness using a finer grit sanding pad. (Odfjell, 2019) Figure 6 presents a diver polishing of a propeller. A clear visual difference can be seen between the polished and untouched surface.

***Figure 6. Diver polishing a propeller. (Odfjell, 2019)***

Propeller blade can bend from an impact with a large object or the ocean floor. Bent propeller tips can be repaired by cold or hot straightening depending on the propeller material and severity of the damage. Hot straightening consists of heating the damaged area and straightening the damage by applying a static force to the propeller. Cold straightening can be used in cases where the blade deformation is small, and the softening of the material is not necessary. (Man Diesel And Turbo, 2020; Germanischer Lloyd Aktiengesellschaft, 2019; Wärtsilä, 2017) Hot straightening of a propeller is presented in Figure 7.

***Figure 7. Hot straightening of propeller. (AEGIR-Marine, 2020)***

Surface damage or localized damage on blade edges caused by cavitation and erosion can be repaired by welding and reshaping or by applying polymer coatings to the damaged area. (Stone Marine Propulsion Ltd, 2019; Belzona International Limited, 2011) The root cause for cavitation damage can be tried to control by altering the leading edge of the propeller. (Carlton, 2012, p. 461) This study evaluates the use of cold spray for cavitation wear repair in Chapter 6.2.

Reduction of the propeller diameter or effective pitch is often called cropping. Cropping consists of reducing the propeller diameter by cutting away and reprofiling the propeller tip. Cropping can be done when the propeller absorbs too much power, or the tip area is severely damaged and cannot be repaired on the spot using other methods. (Carlton, 2012, pp. 459,460) A badly damaged propeller can be repaired by cutting away a section of the propeller, casting a replacement section and welding it to original propeller. (Man Diesel And Turbo, 2020; Wärtsilä, 2017)

Repitching is the modification of the propellers effective pitch in order to alter the power absorption characteristics of the propeller. Repitching can be done by bending the whole propeller blade to change the pitch angle or by modifying the trailing edge of the blade. (Man Diesel And Turbo, 2020; Carlton, 2012; Wärtsilä, 2009)

# 3. OPERATING CONDITIONS

Successful material selection necessitates good understanding of the operating environment and the associated phenomena. For propellers, the most important environmental factor is the sea water which is a highly corrosive media for many metals. This requires the used materials to be naturally resistant to corrosion or to be protected from corrosion. Other prominent issues are cavitation and erosion, impact damage and biological fouling.

## 3.1 Corrosion

Degradation of materials due to corrosion is the main environmental problem associated with maritime equipment (Masi, et al., 2019). Main forms of corrosion in seawater, their progression mechanisms and prevention are presented on the following chapters.

### 3.1.1 Galvanic Corrosion

Galvanic corrosion occurs in electrolytic solution between two contacting metals with different surface potentials (Cicek & Al-Numan, 2011, p. 10). The difference in the material surface potentials creates electron flow, from the more reactive or less noble material to the less reactive material. This galvanic reaction accelerates the corrosion of the less noble material while protecting the more noble material from corrosion. ( Cramer & Covino, 2003, p. 210)

The rate of the galvanic reaction is affected by the surface potential difference between the materials, environment, geometries of the components in galvanic assembly and the polarization behaviour of the materials ( Cramer & Covino, 2003, p. 210).

Increased difference in surface potentials between the materials increases the rate of the galvanic reaction. A general prediction of the rate of the reaction can be made by comparing material pairs using galvanic series table. In practise however the surface potential of a material and its behaviour can be greatly affected by the existing environmental conditions (Cicek & Al-Numan, 2011, p. 210). Generic galvanic series is presented in Figure 8.

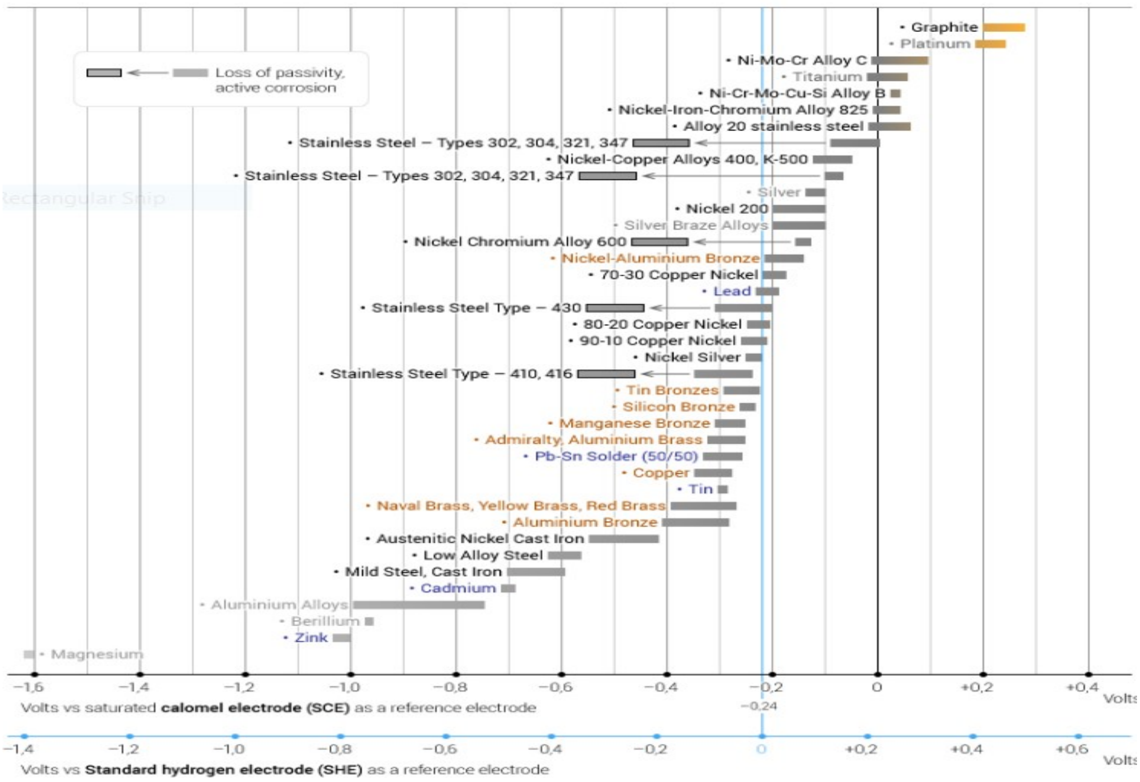


***Figure 8. Galvanic Series table (engineeringclicks, 2017)***

Many other factors such as surface area, distance between the parts and geometric shape of the parts affect the rate of the galvanic reaction. The basic guidelines are that the reaction is increased when the surface area of the more noble metal is large in comparison to the area of the more reactive anode metal, as this increases the current flow per area of the anode. Increasing the distance between the cathode and anode reduces the galvanic reaction as the resistance of the current flow through the electrolyte increases with distance. ( Cramer & Covino, 2003, p. 211)

Galvanic corrosion can be controlled by material selection, barrier coatings, environmental control and design. Materials in the galvanic assembly should be selected so that they are not widely separated in galvanic series unless the more noble material is easily polarized. Galvanic corrosion can be prevented by design by employing electrical insulation between the components, using transition metals, using cathodic protection and designing the assembly, in a way that the surface area ratio between the cathode and anode remains small, and also by avoiding dissimilar metal crevices, such as threaded or riveted joints. ( Cramer & Covino, 2003, p. 213)

Current flow between the materials cause shifts in the material potentials towards the potential of the other material. These shifts alter the potential difference between the materials, thus altering the rate of the galvanic reaction ( Cramer & Covino, 2003, p. 210). Polarization can also shift the material pair’s surface potentials so that the cathode becomes more active than the anode. This will reverse the current flow and cause the more noble material to corrode. ( Cramer & Covino, 2003, p. 211)

Passive materials such as stainless steel and titanium form a dense and well adhering passive oxide layer, that protects the material from corrosion. The oxide layer can be damaged which can lead to localized corrosion, e.g. pitting corrosion, if the passive layer is unable to reform due to lack of oxygen around the damaged area. (Ahmad, 2006)

Noble metal barrier coatings are usually unfavoured as damage or pores in the barrier coating can lead to galvanic corrosion between the coating and the substrate (Ahmad, 2006, p. 131). This problem can be overcome by using cathodic protection.

### 3.1.2 Crevice Corrosion

Crevice corrosion is localised corrosion in gaps, cracks, crevices and between two joining surfaces. The crevice can be from metal to metal contact or from contact with non-metal material or organism such as biological fouling. Stainless steel alloys are prone to crevice corrosion in sea water environment which restricts their use.

Crevice corrosion is suggested to be a four-stage process. In the first stage, the passive material is placed to chloride solution, which begins the formation of a passive layer on the material. Due to this the area within the crevice becomes depleted of oxygen. On second stage, the deoxygenation proceeds outside the crevice, while slow dissolution of the metal happens within the crevice. This causes hydrolysis to happen within the crevice which increases the acidity and thus the aggressiveness of the solution is increased. In third stage the passive film breaks down due to the highly aggressive solution within the crevice. This leads to the final stage where the crevice propagates further. (Ahmad, 2006, pp. 146-147) As deoxygenation is necessary for the process, crevice corrosion is not usually problem in fast moving sea water.

Crevice corrosion can be prevented by minimizing crevice inducing joints in the design, preventing fouling, using cathodic protection, selecting materials that are resistant to crevice corrosion such as titanium and nickel alloys and also by maintaining high water velocity so that local deoxygenation of the solution is not possible. (Ahmad, 2006, p. 149)

### 3.1.3 Pitting Corrosion

Pitting corrosion is the localised corrosion of a metal surface. It forms distinctive pits to the metal surface. Pitting is a major corrosion form in the marine environment as chlorine ions present in sea water cause pitting of steels. (Ahmad, 2006, p. 150)

Pitting corrosion occurs when the oxide layer protecting the metal is damaged locally, exposing the metal. This mechanism of corrosion can be particularly damaging as the areas exposed by the pitting can become anodic sites, which have very small surface area. This creates high current density on the affected area which quickly damages the material further. ( Flemming, et al., 2009) Mechanism of pitting corrosion is very similar to that of crevice corrosion with main difference being the location where the corrosion occurs and the way the passive film is damaged.

### 3.1.4 Stress Corrosion Cracking

Stress corrosion cracking is the failure of a metal resulting from the combined action of tensile stress and corrosion. Many different mechanisms for stress corrosion cracking in four main categories have been suggested. (Ahmad, 2006, p. 194)

1. Film rupture model suggests that passive material's stresses cause the rupture of the passive film. New passive film is grown to the ruptured area which alters the mechanical properties of the material near the crack. This process of rupture and reformation of the passive film is repeated which accelerates the crack propagation. On other theories it has been suggested that a lack of passive film at the tip of the crack causes localised corrosion which helps propagate the crack further. (Ahmad, 2006, p. 195)

2. Mechano-electrochemical model suggests that the material contains paths which are naturally suspectable to corrosion. Localised corrosion propagates through these paths which induces cracks to the material. The model suggests that the use of cathodic protection prevents stress corrosion cracking. (Ahmad, 2006, p. 194)

3. Embrittlement model suggests that electrochemical process embrittles the material near the surface or crack tip. This loss of ductility amplifies the crack propagation which leads to premature failure of the part. (Ahmad, 2006, p. 195)

4. Absorption model claims that the absorption of damaging species weakens the cohesive bonds between the surface metal atoms, which degreases the energy needed for crack formation. (Ahmad, 2006, p. 195)

In case of the propeller application stress corrosion cracking can be prevented mainly by material selection and lowering the loading of the material, as the environmental conditions cannot be affected. Proper coating material selection can prevent the crack formation and propagation to the base metal, which allows the base material to be more highly loaded.

## 3.2 Cavitation wear

Cavitation in a propeller happens, when the local pressure falls below the vapour pressure of the water at the current water temperature. This causes a bubble to form on the surface of the propeller blade. As the propeller is turning, the bubble is being moved to location where the local pressure is again higher than the current vapour pressure of water, which causes the bubble to collapse. This process is being reproduced in quick succession as the propeller rotates (Pemberton & Stokoe, 2012, p. 145). Cavitation erodes the propeller surface and creates deep pits and holes to the propeller material. Usually cavitation damage progresses to a severe state during months or years, although in some cases severe damage has occurred in just few hours of operation (Carlton, 2012, p. 235). Example of cavitation damage on propeller blade is presented in Figure 9.

***Figure 9. Cavitation damage on a propeller blade. (Stone Marine Propulsion Ltd, 2019)***

In addition to the structural damage, cavitation reduces the efficiency and thrust of the propeller while causing excessive noise and vibration. Cavitation is usually mitigated by reducing the rotational speed of the propeller and reducing the pressure differential or loading of the propeller. Both actions are detrimental for the efficiency of the propulsion system, as a larger propeller is required for an equal thrust rating. (Pemberton & Stokoe, 2012, p. 146) Cavitation bubble formation on propeller is presented in Figure 10.

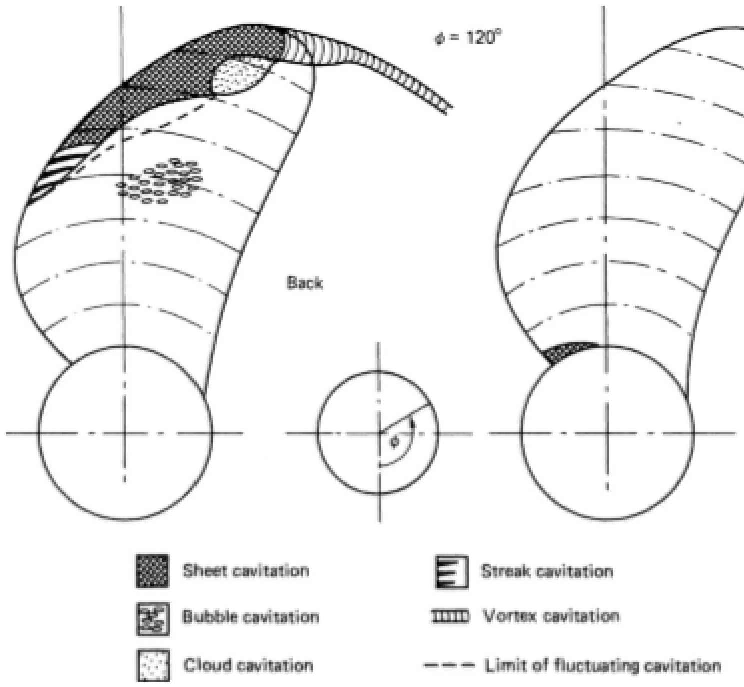


***Figure 10. Sketch of typical cavitation on a propeller. (Carlton, 2012, p. 244)***

According to Carlton, cavitation damage in blade surface progresses in three distinctive stages. On the first stage, cavitation erodes the blade surface to orange peel texture. In many cases the cavitation damage ceases to progress further during the operating life of the vessel. On other cases the damage further progresses to light erosion and possibly further to severe erosion, in which deep cavities or through holes are formed to the propeller surface (Carlton, 2012, p. 235).

It is believed that the most damaging mechanism of cavitation is the bubble collapse and micro jet formation close to the surface, which then impinges the material. According to studies, these microjets can develop impact pressure of over 100 MPa for duration of over 10 μs. This subsequently work hardens and embrittles the material, which through cracking leads to erosion of the material. (Carlton, 2012, p. 237)

Figure 11 presents microhardness measurement results taken from nickel aluminium bronze propeller sample. The measurements for “Traverse 1” were taken from an area at propeller suction surface that had suffered from severe cavitation damage. “Traverse 2” contains measurements from a suction surface area that had suffered from less severe cavitation damage. Measurements for “Traverse 3” were taken from pressure surfaces which should not be subjected to cavitation. The measurements show that the hardening of the material was more severe in the areas of more severe cavitation damage and that the pressure surface was not hardened as it does not suffer from cavitation. Measurements also show that the work hardening from cavitation affects the material to depths of up to 3 mm from the surface. (Carlton, 2012, p. 237)

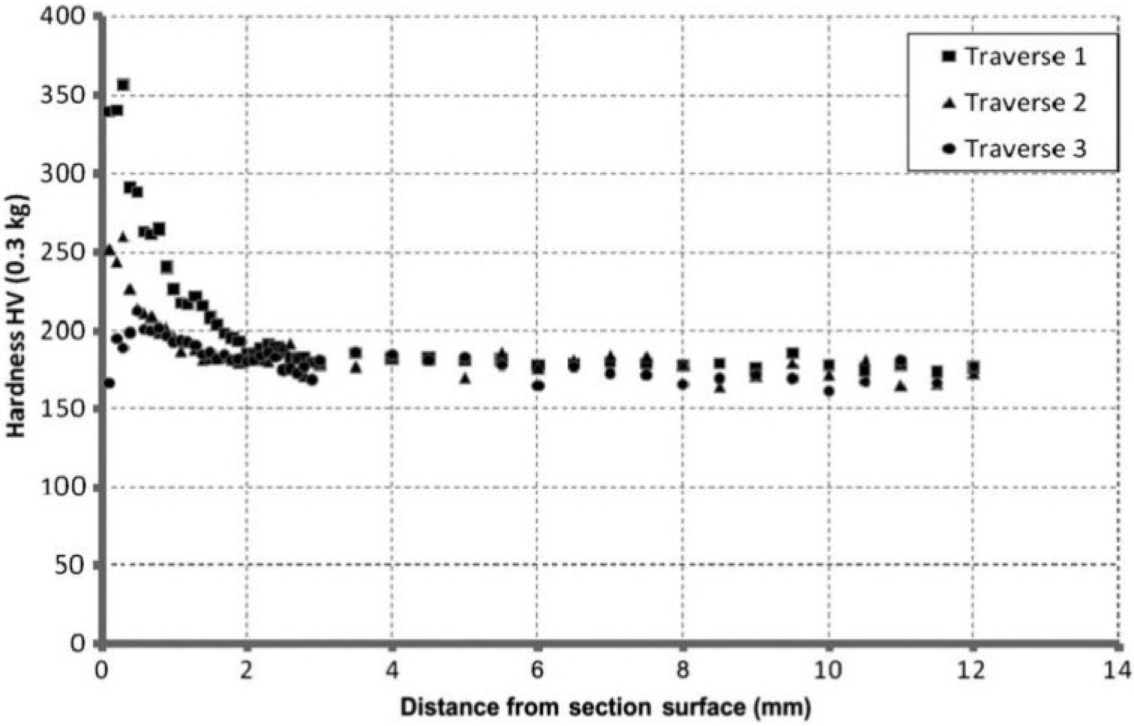


***Figure 11. Micro-hardness measurements taken from nickel-aluminium bronze propeller blade sample. (Carlton, 2012, p. 238)***

According to studies review by Sreedhar, materials resistance to cavitation has been estimated to depend on the ultimate tensile strength, fatigue strength, hardness, and fracture toughness coefficient of the material. Sreedhar also states that the modelling of cavitation erosion is difficult as mechanical properties of a bulk material are tested under near static loading conditions, while cavitation loads the material under very high strain rates. (Sreedhar, et al., 2017) Thus, mechanical properties of the bulk material have a limited use for predicting the materials resistance to cavitation erosion.

To conclude, while cavitation can be reduced by a good propeller design, the propeller is expected to encounter cavitation during its operating life. Protective properties of noble metal barrier coatings relay on the integrity of the coating. Therefore, the coating must have good resistance to erosion by cavitation. Areas of expected cavitation should also have enough thickness to sustain some amount of erosion.

## 3.3 Impact loading and Abrasion

Impact loading of the propeller describes the contact with other objects in the ocean. Impact loading is an especially prominent design factor in arctic and ice-breaking vessels as they frequently encounter blocks of ice. Ice contact loading describes the mechanical loading of the ice by cutting, milling, crushing, and bending by the propeller. Additional hydrodynamic loads are caused by the suction due to restricted water inflow by the ice blocks, and by the squeezing of ice and water between the propeller blade and the ice block. Figure 12 illustrates the cause of both loading methods.

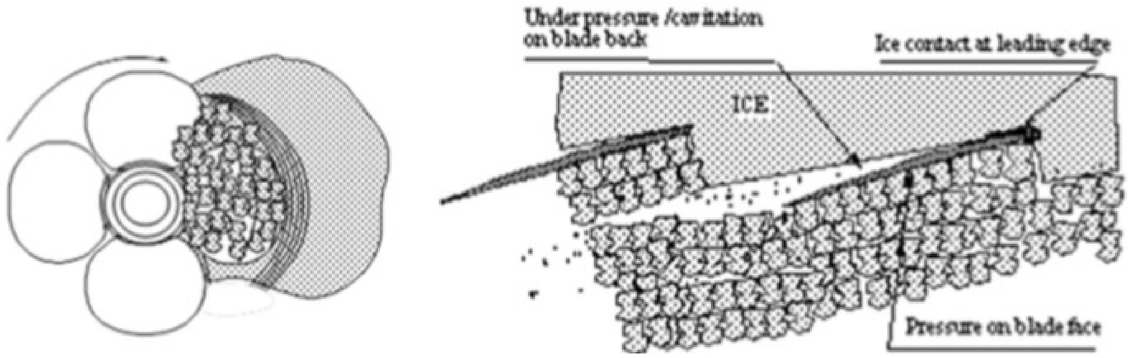


***Figure 12. Ice loading of the propeller. (Kinnunen, et al., 2015)***

Ice loading of the propeller has been studied using both analytical methods and practical measurements. Measurements have been conducted using strain gauges located either in propeller blade or in propeller shafts. On later case the ice loading has been implicitly calculated using lumped mass model of the propulsion system (Ikonen, et al., 2015).

In practice, dimensioning of the propulsion system is done according to the classification society rules regulating the design of the vessel, such as DNV GL. Modelling of the ice of the propeller blade behaviour on ice impact loading is a complex topic itself, and it is thus left out of the scope of this study. According to the class rules, materials used to fabricate propellers for arctic use need to have elongation of 15% or more, and an average impact energy of 20 J or more from three Charpy V test at -10 ºC. (DNV-GL, 2015)

In addition to ice loading abrasive media such as sand particles are floating in the water, especially near coasts. These floating particles can erode the propeller blade so their effect on the propeller surface must be taken in consideration. (Carlton, 2012).

## 3.4 Marine Biological Fouling

Marine biological fouling is the accumulation of micro-organisms, plants and animals on the artificial surface immersed in sea water. Fouling is a well know problem for mariners with the phenomenon being described already by Greek philosopher Plutarch, who described the impact of fouling and its prevention in his essays: “it is probable that it (ship) lightly glides, and as long as it is clean, easily cuts the waves; but when it is thoroughly soaked, when weeds, ooze, and filth stick upon its sides, the stroke of the ship is more obtuse and weak; and the water, coming upon this clammy matter, doth not so easily part from it; and this is the reason why they usually calk their ships.” (Plutarch, 2009)

Fouling causes multitude of problems for the vessel and environment:

- Fouling increases the surface roughness of the ship’s surfaces, which leads to increase in fluid friction losses. The increase in friction reduces the fuel efficiency of the vessel and leads to loss of manoeuvrability. Accumulated fouling necessitates the removal of the accumulation by dry-docking the vessel, which wastes time and resources. (Yebra, et al., 2004)
- Fouling can damage the protective coatings of the ship and render the surfaces prone to corrosion.
- Fouling transports non-native species to new locations with the ship, which can have negative impact on the local environment and wildlife.

Many measures have been developed to prevent fouling in ships structures. These methods are widely employed, and they are more effective than what can be archived with material selections only (Yebra, et al., 2004). Still it is important to consider fouling while selecting the coating material as the fouling can have adverse behaviour on the corrosion resistance of the material ( Flemming, et al., 2009).

According to Flemming et al. two mechanisms have been suggested, by which microbial interaction from marine biological fouling can accelerate the corrosion of passive materials. It is suggested that the biomineralized manganese oxides deposited by the microbes can raise the potential of the passive metal above the pitting potential. Alternatively, the fouling has been suggested to cause localized damage to the passive oxide layer resulting in decrease in the pitting potential of the material. ( Flemming, et al., 2009)

# 4. MATERIALS

This chapter discusses currently used propeller materials, alternative materials for coated propeller and properties of cold sprayed coating materials. Ship propellers have been manufactured from various materials from once popular cast iron to now commonly used bronze and stainless-steel alloys. (Carlton, 2012, p. 385) More exotic materials like fibre reinforced plastics have also been used in specialised use cases, such as in military submarines, where the high damping property of carbon fibre has allowed the manufacturing of propellers with lower noise emission. (Carlton, 2012, p. 385; Nakashima Propeller Co., Ltd, 2015) Figure 13 categorises the used propeller materials.

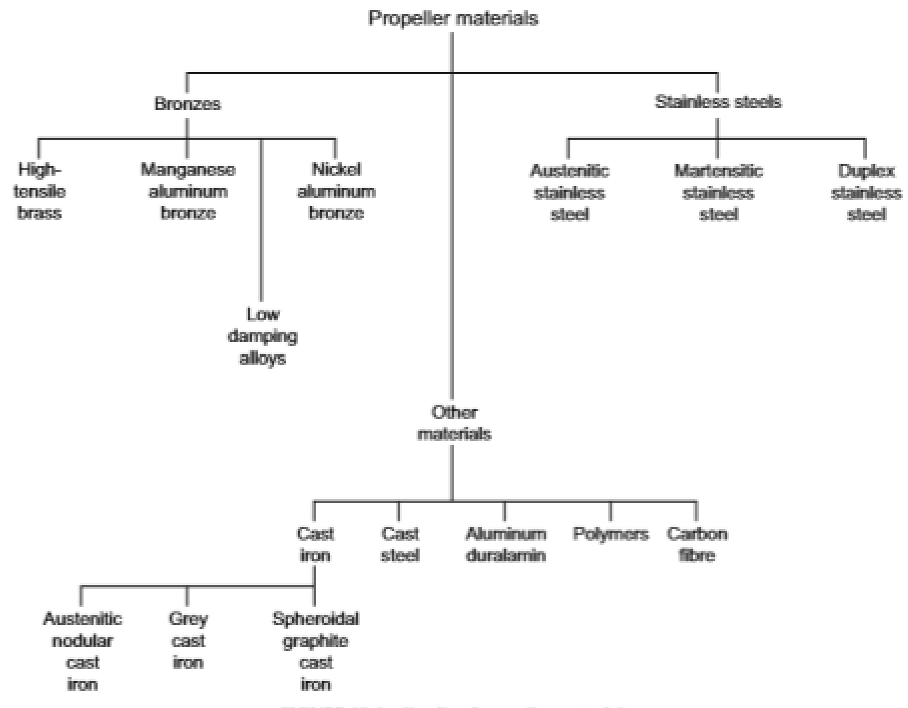


***Figure 13. Propeller materials. (Carlton, 2012, p. 386)***

Modern propellers are dominantly manufactured from bronze alloys with nickel aluminium bronze being the most popular propeller material. According to Carlton nickel aluminium bronze propellers account to over 80 percent of propellers. Second notable propeller material is stainless steel, which is commonly used in ice class propellers that require higher strength than attainable with bronze materials. (Carlton, 2012, p. 385)

With the nickel aluminium bronze and stainless-steel alloys being the most common propeller materials currently in use in propellers, their properties are discussed further in the following chapters to give a benchmark to which alternative propeller materials can be compared.

## 4.1 Current Propeller Materials

This chapter discusses the basic properties of the most used propeller materials: nickel aluminium bronze and martensitic stainless steel. Table 1 presents standard propeller materials and their minimum properties according to Lloyd's Registers.

***Table 1. Materials for propeller manufacturing. (Lloyd's Register, 2013)***

| Material | SI units | | | Metric units | | |
|---|---|---|---|---|---|---|
| | Specified minimum tensile strength $N/mm^2$ | *G* Density $g/cm^3$ | *U* Allowable stress $N/mm^2$ | Specified minimum tensile strength $kgf/mm^2$ | *G* Density $g/cm^3$ | *U* Allowable stress $kgf/mm^2$ |
| Grey cast iron | 250 | 7,2 | 17,2 | 25 | 7,2 | 1,75 |
| Spheroidal or nodular graphite cast iron | 400 | 7,3 | 20,6 | 41 | 7,3 | 2,1 |
| Carbon steels | 400 | 7,9 | 20,6 | 41 | 7,9 | 2,1 |
| Low alloy steels | 440 | 7,9 | 20,6 | 45 | 7,9 | 2,1 |
| 13% chromium stainless steels | 540 | 7,7 | 41 | 55 | 7,7 | 4,2 |
| Chromium-nickel austenitic stainless steel | 450 | 7,9 | 41 | 46 | 7,9 | 4,2 |
| Duplex stainless steels | 590 | 7,8 | 41 | 60 | 7,8 | 4,2 |
| Grade Cu 1 Manganese bronze (high tensile brass) | 440 | 8,3 | 39 | 45 | 8,3 | 4,0 |
| Grade Cu 2 Ni-Manganese bronze (high tensile brass) | 440 | 8,3 | 39 | 45 | 8,3 | 4,0 |
| Grade Cu 3 Ni-Aluminium bronze | 590 | 7,6 | 56 | 60 | 7,6 | 5,7 |
| Grade Cu 4 Mn-Aluminium bronze | 630 | 7,5 | 46 | 64 | 7,5 | 4,7 |

It is worth noting that while cast iron and steel materials are recognised and once used materials for propeller fabrication, their poor corrosion resistance heavily restricts the allowable design stresses. (Lloyd's Register, 2013; Carlton, 2012)

### 4.1.1 Nickel Aluminium Bronze

Nickel aluminium bronze is the most used material for propeller fabrication as it has overall good corrosion resistance, good mechanical properties and fabricability while being relatively cost efficient when compared to other corrosion resistant materials (Carlton, 2012; Strang, 2010). Other notable properties of nickel aluminium bronze are its good resistance to cavitation erosion and its well-known resistance to biological fouling. Both cavitation erosion and biological fouling can ruin the long-term propulsive efficiency of the propeller. (Stone Marine Propulsion Ltd, 2019; Krebs, 2016; Strang, 2010; Flemming, et al., 2009)

Classification societies dictate the composition and mechanical properties which the propeller alloys must meet. Minimum mechanical properties for standard bronze alloys used in propeller manufacturing according to Germanischer Lloyd Aktiengesellschaft as measured from separately cast test specimen are presented in Table 2.

***Table 2. Mechanical properties of cast bronze propeller alloys. (Germanischer Lloyd Aktiengesellschaft, 2019)***

| Casting grade | $R_{p0,2}$ [N/mm²] min. | $R_m$ [N/mm²] min. | A [%] min. |
|---|---|---|---|
| CU1 | 175 | 440 | 20 |
| CU2 | 175 | 440 | 20 |
| CU3 | 245 | 590 | 16 |
| CU4 | 275 | 630 | 18 |

Nickel aluminium bronzes are somewhat simpler materials to repair as they do not always require stress relieve heat treating to be done after welding repair. (DNV GL, 2019)

### 4.1.2 Stainless Steels

Stainless steels and especially their martensitic alloys are commonly used propeller materials, when higher resistance to impact damage is required, which is the case with propellers used in arctic vessels and ice breakers. (Carlton, 2012, p. 391). Stainless steel propellers are significantly more expensive than bronze propellers, with the material also being less resistant to corrosion and cavitation, with pitting, stress corrosion cracking, crevice corrosion and intergranular corrosion being prominent problems with the material. (Carlton, 2012; Strang, 2010; Ahmad, 2006)

Martensitic stainless steels are usually used in propeller manufacturing as they feature good strength when compared to austenitic steels, with the yield strength of the martensitic steels being around 500 MPa, and ultimate tensile strength being in 760-960 MPa (Germanischer Lloyd Aktiengesellschaft, 2019). Martensitic stainless steels are however more prone to corrosion than austenitic stainless steels (Féron, 2001, p. 58).

Standard stainless-steel propeller alloys require a heat treatment to archive the required mechanical properties. Heat treatment is also necessary after repairing stainless steel propeller by welding as the high heat input alters the microstructure of the heat affected zone. Table 3 presents the heat-treating temperatures and resulting microstructure for the standard stainless-steel alloys used for propeller fabrication. (Germanischer Lloyd Aktiengesellschaft, 2019)

***Table 3. Tempering of stainless-steel alloys used in propeller fabrication (Germanischer Lloyd Aktiengesellschaft, 2019)***

| Alloy type | Quenching | | Tempering | Microstructural constitution |
|---|---|---|---|---|
| | Temperature [°C] | Quenching medium | Temperature [°C] | |
| 12Cr1Ni | 1000 – 1060 | Air [1] | 680 – 730 | Martensitic-ferritic |
| 13Cr4Ni | 1000 – 1050 | Air [1] | 590 – 620 | Martensitic-ferritic |
| 16Cr5Ni | 1020 – 1070 | Air [1] | 580 – 630 | Martensitic-ferritic |
| 19Cr11Ni | 1080 – 1150 | Water / Air [1] | — | Austenitc |

[1] Cooling in air to be as rapid possible.

Mechanical properties of the resulting tempered stainless-steel alloys are presented in Table 4. Martensitic stainless-steel materials have a proof strength around 200 MPa higher than that of nickel aluminium bronze materials.

***Table 4. Mechanical properties of stainless-steel alloys used in propeller fabrication (Germanischer Lloyd Aktiengesellschaft, 2019)***

| Alloy type | $R_{p0,2}$ [N/mm²] min. | $R_{p1,0}$ [N/mm²] min. | $R_m$ [N/mm²] | A [%] min. | KV [1] [J] min. | Hardness (Guide values) [HB] |
|---|---|---|---|---|---|---|
| 12Cr1Ni | 355 | — | 540 – 690 | 18 | 45 [3] | 200 |
| 13Cr4Ni | 550 | — | 760 – 960 | 15 | 50 [3] | 260 |
| 16Cr5Ni | 540 | — | 760 – 960 | 15 | 60 [3] | 260 |
| 19Cr11Ni | — | 210 (220) [2] | 440 – 640 | 30 | 60 (80) [2] | 160 |

[1] Average from 3 Charpy V-notch specimens (testing temperature = room temperature).
[2] Values in parenthesis are applicable to an alloy type with a maximum 0,030 % C and 0,12 – 0,20 % N.
[3] According to the Finnish-Swedish Ice Class Rules as regards ships contracted for construction on 1. January 2010 or thereafter an average impact energy value of 20 J is to be obtained at –10 °C.

Elongation of the martensitic stainless steels is less when compared to bronze. Class rules require the elongation of martensitic stainless steels to be tested. (Germanischer Lloyd Aktiengesellschaft, 2019)

## 4.2 Alternative Propeller Materials

To be successful, the alternative propeller material must bring financial benefit to the end user over using a conventional propeller material. This benefit can be archived by either by reducing the purchase price of the propeller or by fabricating the propeller from stronger material thus making it possible to increase the efficiency of the propeller and then lessen the operating costs of the vessel. Rate of return of investment capital for given increase in propeller efficiency and increase in propeller price is calculated in Chapter 6. From this analysis it can be concluded that the increase in justifiable propeller cost for given efficiency gain is rather small. This practically restricts the materials to ones with cost less or equal to the current propeller materials as costs must also be reserved for the coating. Due to this reason the propeller cannot be manufactured from otherwise interesting materials such as nickel alloys or titanium as is presented in relative cast cost index in figure 14.

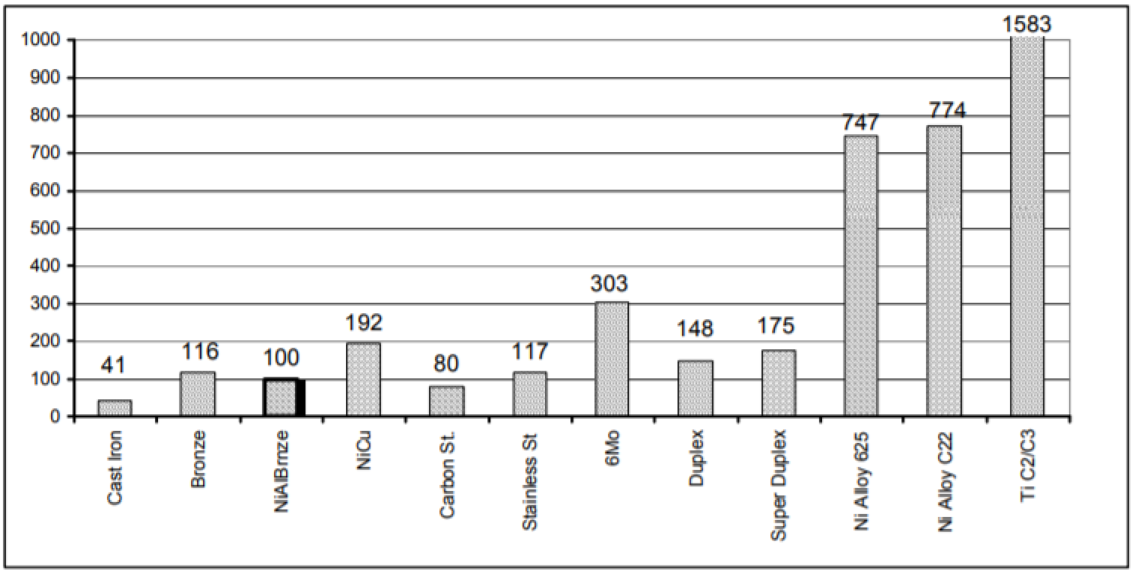


***Figure 14. Relative cast cost index. (Strang, 2010)***

Aside price, the mechanical properties of the material are an important consideration as they dictate the geometry to which the propeller can be designed for. Stronger material allows more efficient geometries to be archived, so the strength of the material should match or exceed those of current propeller materials so that efficiency losses and thus financial losses can be prevented. Figure 15 presents the yield and tensile strength of competing materials in as cast state. Steels, nickel alloys and titanium alloys can match the yield strength of nickel aluminium bronze in cast state. (Strang, 2010) For many materials much higher strength levels can be archived by heat treating. (Blair, 1990)

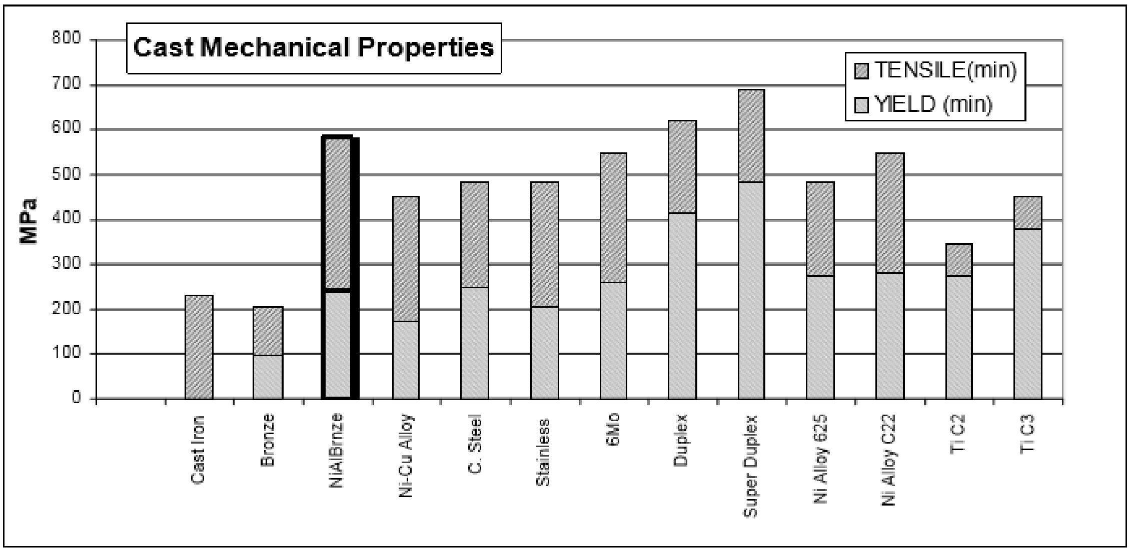


***Figure 15. Yield and tensile strength comparison. (Strang, 2010)***

By assessing the comparative costs and mechanical properties of the materials, mild steels and steel alloys are concluded to be the most promising candidates as an alternative propeller material for a coated propeller. It is worth mentioning, while from cost standpoint cast iron would be an interesting option, the material tends to crack from impact while being difficult to repair, so it is not ideal for propeller use. (Carlton, 2012, p. 392; Stone Marine Propulsion Ltd, 2020)

## 4.3 Coating Materials

This chapter discusses cold sprayable materials which could be useful for coating, manufacturing, and repairing of the thruster parts. The materials are evaluated by their suitability for the given application, coating material properties and for the sprayability of the material using currently available commercial equipment. Table 5 presents sprayability of various materials.

***Table 5. Spreayability of various materials by the Cold Spray Process. (Assadi, et al., 2016)***

| | | $T_g$ = 400 °C, $p_g$ = 30 bar | | | | $T_g$ = 800 °C, $p_g$ = 40 bar | | | |
|---|---|---|---|---|---|---|---|---|---|
| Material | $v_{cr}(T_p$=20°C) | Material | $\eta\,(d_p$=30µm) | Material | $\eta\,(d_p$=50µm) | Material | $\eta\,(d_p$=30µm) | Material | $\eta\,(d_p$=50µm) |
| Zinc | 339 | Zinc | 2.18 | Zinc | 2.15 | Zinc | - | Zinc | - |
| Tantalum | 447 | Aluminium | 1.44 | Aluminium | 1.50 | Mg-AZ91 | - | Mg-AZ91 | - |
| Copper | 451 | Copper | 1.29 | Al-6061 | 1.35 | Al-7075 | - | Al-7075 | - |
| Aluminium | 482 | Al-6061 | 1.28 | Copper | 1.27 | Al-6061 | - | Al-6061 | - |
| CuZn30 | 505 | CuZn30 | 1.17 | Magnesium | 1.23 | Aluminium | - | Magnesium | - |
| Al-6061 | 556 | Al-7075 | 1.16 | Al-7075 | 1.21 | Magnesium | - | Aluminium | - |
| Niobium | 564 | Magnesium | 1.11 | Mg-AZ91 | 1.13 | Copper | 1.92 | Copper | 1.86 |
| Nickel | 574 | Tantalum | 1.04 | CuZn30 | 1.11 | CuZn30 | 1.85 | CuZn30 | 1.73 |
| CuAl9Ni2 | 594 | CuAl9Ni2 | 0.99 | Tantalum | 0.96 | CuAl9Ni2 | 1.51 | CuAl9Ni2 | 1.43 |
| Iron | 596 | Mg-AZ91 | 0.99 | CuAl9Ni2 | 0.95 | Nickel | 1.35 | Nickel | 1.25 |
| Molybdenum | 605 | Nickel | 0.97 | Nickel | 0.91 | Tantalum | 1.33 | Iron | 1.24 |
| Magnesium | 607 | Niobium | 0.96 | Iron | 0.91 | Iron | 1.32 | Tantalum | 1.22 |
| Steel 409 | 630 | Iron | 0.95 | Niobium | 0.91 | Steel 409 | 1.27 | Steel 316L | 1.19 |
| Steel 316L | 655 | Steel 409 | 0.91 | Steel 316L | 0.86 | Niobium | 1.25 | Steel 409 | 1.19 |
| Al-7075 | 658 | Steel 316L | 0.88 | Steel 409 | 0.86 | Steel 316L | 1.24 | Niobium | 1.18 |
| Titanium | 712 | Molybdenum | 0.86 | Titanium | 0.84 | Titanium | 1.17 | Titanium | 1.15 |
| Mg-AZ91 | 726 | Titanium | 0.85 | Molybdenum | 0.81 | Molybdenum | 1.12 | Molybdenum | 1.05 |
| TiAl6V4 | 1013 | TiAl6V4 | 0.60 | TiAl6V4 | 0.59 | TiAl6V4 | 0.83 | TiAl6V4 | 0.82 |

The coating can provide protection by acting as a barrier between the electrolyte and the substrate material and in case of sacrificial coatings, provide galvanic protection for the substrate. Noble coating materials such as titanium, stainless steel and nickel alloys provide protection for the substrate if the coating is intact. Defects such as pores, pits and cracks will lead to a development of galvanic cell in which the substrate will act as anode. This will lead to rapid corrosion of the substrate material. (Tucker, 2013) Figure 16 presents HVOF sprayed nickel coatings which has suffered from corrosive attack permitted by through pores on otherwise dense appearing coating.

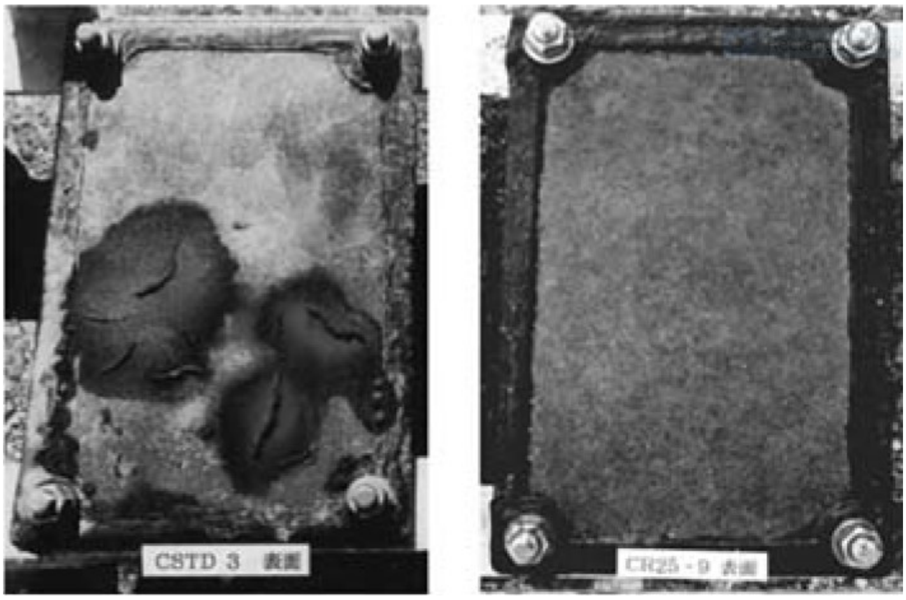


***Figure 16. Steel substrate coated with nickel using HVOF process after 3-month submersion to sea water. (Kuroda & Sturgeon, 2005)***

Sacrificial coatings made from zinc and aluminium protect the substrate even if the coating does not fully cover the substrate (Tucker, 2013). Thermally sprayed sacrificial coatings have been used with good success on marine environment for decades. These materials are however less resistant to cavitation, erosion, and impact damage which limits their use in fast flow velocities encountered in moving vessels. Zinc is also consumed in seawater by uniform corrosion which limits the lifetime of submerged zinc coatings. For these reasons sacrificial coatings are not discussed in depth. Comparison of the corrosion resistance of materials used in marine applications is provided in Table 6.

***Table 6. Comparison of the corrosion resistance of materials. (Strang, 2010)***

| Arbitrary scale, higher is better | General Corrosion | Pitting Corrosion | Crevice Corrosion | Erosion Corrosion | Cavitation | Stress Corrosion |
|---|---|---|---|---|---|---|
| Bronze | 8 | 9 | 9 | 7 | 5 | |
| NiAlBrnze | 9 | 10 | 8 | 8 | 8 | 10 |
| Ni-Cu Alloy | 10 | 5 | 2 | 10 | 8 | ? |
| Carbon | 3 | 3 | | | 2 | |
| Stainless | 10 | 4 | 3 | 10 | 7 | 8 |
| 6Mo | 10 | 9 | 8 | 10 | 8 | 8 |
| Duplex | 10 | 5 | 4 | 10 | 8 | 9 |
| Superduplex | 10 | 9 | 8 | 10 | 8 | 9 |
| Ni Alloy 625 | 10 | 13 | 12 | | 13 | |
| Ni Alloy C22 | 10 | 14 | | | 10 | |
| Titanium | 10 | 15 | 10 | | 9 | |

As can be expected from a current propeller material, the nickel aluminium bronze has overall good resistance against all forms of corrosion and erosion present in sea water. In addition, nickel aluminium bronze has good resistance to biological fouling due to the high copper content of the material ( Flemming, et al., 2009; Strang, 2010). Nickel alloys and titanium also have an excellent overall resistance to all forms of corrosion in sea-water. (Crook, 2005; Totten & MacKenzie, 2016) These materials are further discussed for their potential use for noble barrier coating of components. Stainless steel is discussed for its use in noble coatings and in repair of arctic propellers.

### 4.3.1 Titanium

Titanium is a commonly used material in aerospace applications as it exhibits good mechanical properties while having low density. Titanium is also well known to form a very stable oxide film which protects the material from corrosion even in highly corrosive environments. For this reason, titanium is also commonly used in process industry. (Totten & MacKenzie, 2016) Titanium has excellent resistance against corrosion including pitting and crevice corrosion in sea water. Titanium is also noted to have good resistance to erosion from cavitation and high velocity particles in sea water. (Totten & MacKenzie, 2016; Strang, 2010) Titanium is a difficult material to manufacture. Heat treating and casting of titanium must be done in vacuum or inert atmosphere. Machining of titanium is also difficult, as the material has low thermal conductivity, which results in heat build-up at the machined area. Titanium is also very suspectable to work hardening by the cutting action. (Chandler, 1989)

Both free standing structures and coatings have been done using cold spray method. (Huang, et al., 2015; Titomic, 2020) Study conducted on the mechanical properties of as sprayed and heat-treated titanium materials by Plasma Giken showed that archiving dense coating with good mechanical properties is difficult with titanium by using cold-spray method. Titanium particles showed little deformation which caused the sprayed material to be porous even after recrystallization in high temperatures. Microstructure of the titanium deposits are presented in Figure 17. (Huang, et al., 2015)

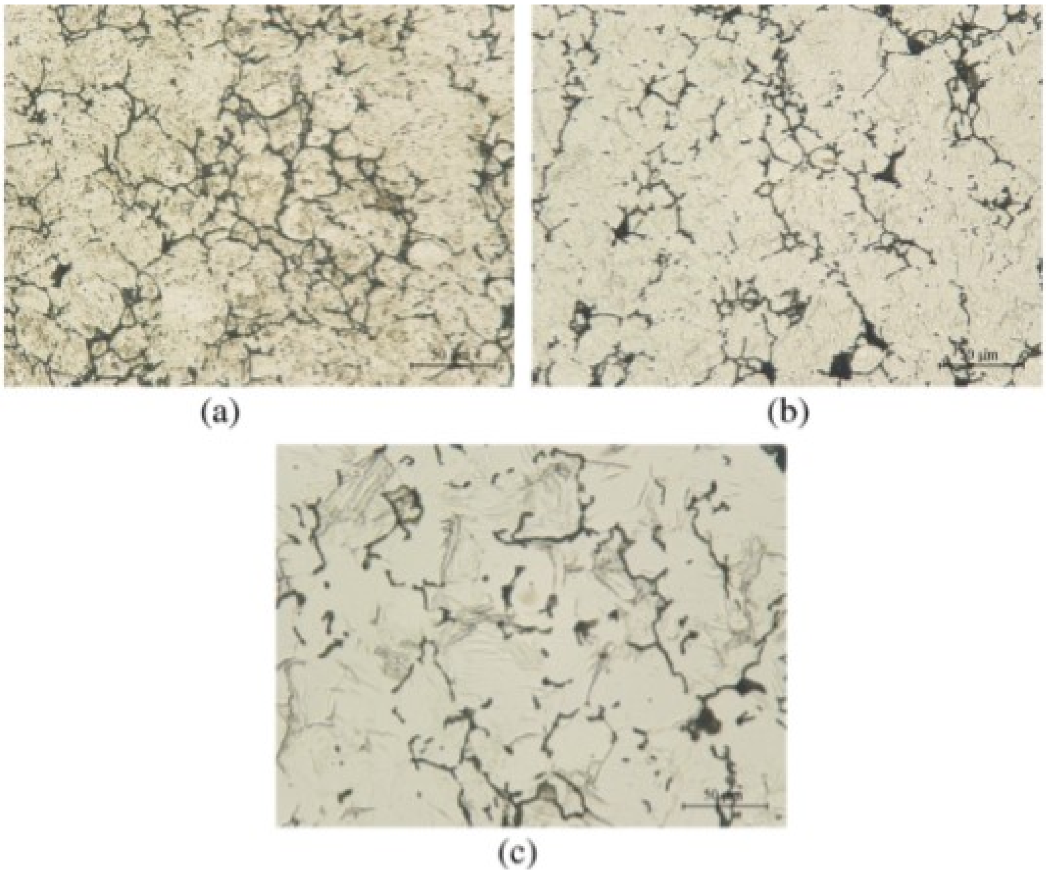

***Figure 17. Microstructure of cold sprayed titanium coating. As sprayed (a), heat treated at 600 (b) and 1000 °C (c). (Huang, et al., 2015)***

Lupoi, et al. have formed titanium coatings on steel substrate using supersonic laser deposition (SLD) process where the sprayed material and substrate surface are heated using laser while spraying the coating. The study claims that the method can archive dense coatings with improved mechanical properties when compared to cold spray. (Lupoi, et al., 2011) As SLD process does not rely entirely on the high particle velocity, nitrogen carrier can be used for titanium coatings, which offsets the costs incurred by the more complex process. Microstructure of SLD process can be found in Figure 18.

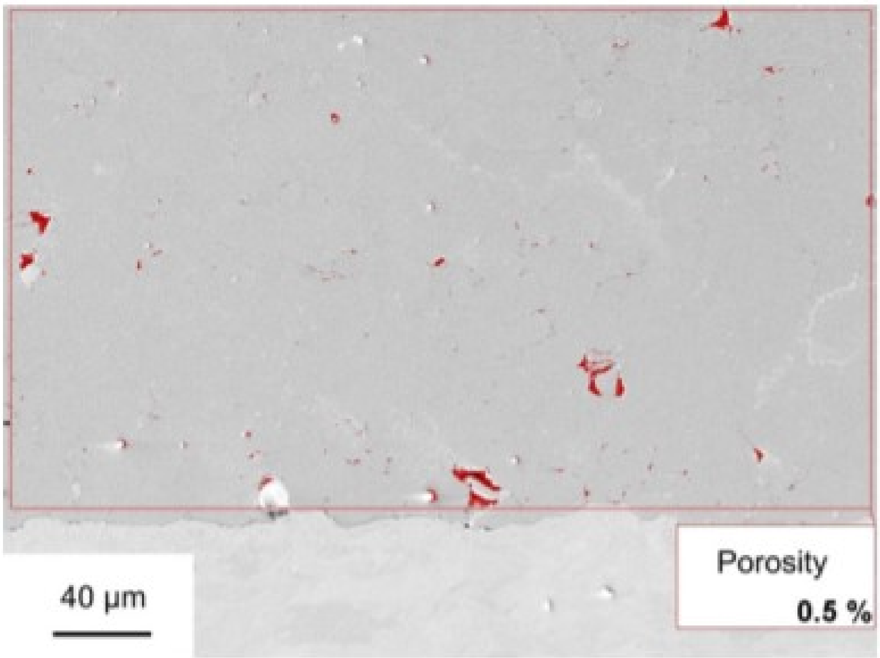


***Figure 18. Microstructure of titanium coating deposited using laser assisted cold spray process. (Bray, et al., 2009)***

Titanium coating deposited using the SLD process is visibly denser to that done using normal cold spray process, even after the material has been heat treated. This suggests that in case of titanium, the use of SLD process would be favourable.

While titanium would be an excellent material for propeller coating judging by its material properties, the material is difficult to deposit using cold spray. Protective properties of barrier coatings rely on the defect free nature of the coating, so porosity in the coating cannot be permitted. Other spray processes such as SLD process have been developed, which could aid archiving dense coatings from titanium, but such processes are yet to be commercialized.

### 4.3.2 Nickel Alloys

Common characterises of nickel alloys are their excellent corrosion resistance, good strength and toughness and the ability to withstand high temperatures. Nickel is also an important plating material in many industries. Nickel alloys are a good choice for marine use as they are resistant to corrosion and cavitation errosion, altough crevice corrosion and pitting can occur in stagnant flow conditions. Nickel alloys are also less suspectable to stress cracking corrosion than stainless steels in marine environment. (Rebak, 2011; Crook, 2005) For use in sea water environment nickel is commonly alloyed with copper to increase its resistance to corrosion in sea water. These alloys are commonly referred by their trademark Monel, which is owned by Special Metals Corp. In addition to their corrosion resistance nickel-copper alloys are also noted to have good resistant to cavitation erosion. (Strang, 2010; Haynes International Inc, 2007)

Many studies have been conducted about cold spraying nickel alloys such as Ni-Cu and Inconel 625 have demonstrated that dense nickel alloy coatings can be deposited using cold spray. Koivuluoto, et al. studied corrosion resistant properties of Ni and NiCu coatings, which were deposited using high pressure cold spray. On certain samples the powder was blended by volume to 50/50 mixture of NiCu and $Al_2O_3$ grit to provide shot peening effect to the deposit in order to compact the coating. According to the electrochemical tests, the corrosion resitance of the Ni and NiCu coatings was very close to that of bulk material, which indicated that good quality barrier coatings can be archived using high pressure cold spray. The use of $Al_2O_3$ grit was found to improve the coating quality by increasing the density of the coating both by hammering the coating and by allowing higher gas temperatures to be used without clogging the nozzle of the spray gun. (Koivuluoto, et al., 2014) On a further study a 80h Corrodkote accelerated corrosion test was conduced to evaluate the impermeability of the coatings. The results found that heat treatment in 600 °C for two hours, and the mixing of powder with $Al_2O_3$ had a positive impact on the coating quality. Test specimens after the corrodkote tests are presented in Figure 19.

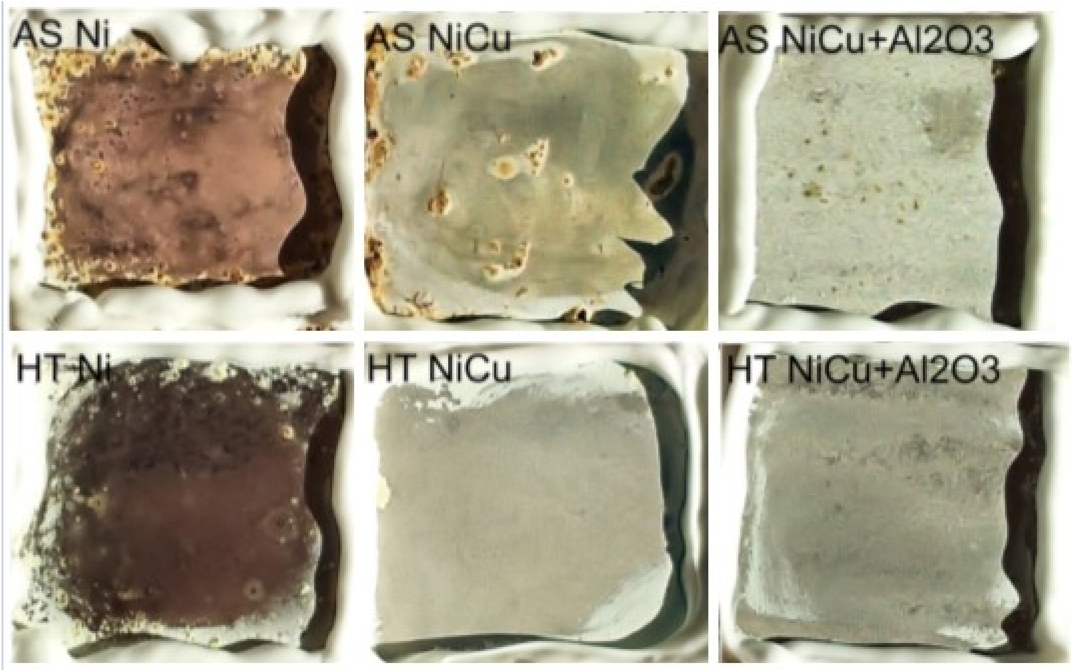


***Figure 19. As sprayed and heat-treated Ni based coatings after 80h Corrodkote test. (Koivuluoto, et al., 2015)***

Pontarollo et al. studied the corrosion resistance of cold sprayed Inconel 625 coatings and compared the properties to those produced by HVOF process. Three samples were prepared using different settings and powder sizes. The best results were archived with sample C1 which featured coarse powder and thickest 480 µm thick coating. The corrosion current and interpolated corroion rate of the samples can be seen in Table 7. The corrosion rate of the best cold sprayed coating is half ot the coating produced with HVOF process. (Pontarollo, et al., 2011)

***Table 7. Corrosion current and interpolated corrosion rate of bulk and sprayed Inconel 625. (Pontarollo, et al., 2011)***

| Sample | $i_{corr}$ [µA/cm$^2$] | CR [mm/y] |
|---|---|---|
| Inconel 625 bulk | 95 | 0.95 |
| AISI 316L SS bulk | 116 | 1.36 |
| Inconel 625 Commercial HVOF | 156 | 1.82 |
| C1 | 97 | 0.99 |
| C2 | 286 | 1.80 |
| C3 | 176 | 2.92 |

Wei et al. studied the corrosion resistance of cold sprayed nickel coatings which were produced using high pressure cold spray to magnesium substrate. The powder used was blended with large AISI 410 stainless steels particles to provied shot peening effect to the coating. The study found that the produced coatings were very dense and had no visible pores or inter-particle cracks. The coatings had avarage bonding strenght of 65.4 MPa, which is noted to be around 5 times higher than what is optainable using electroless nickel plating in magnesium substrate. A long term corrosion test was done by submerging the coated sample to 3.5wt.% NaCl solution for 1000 h. The results of the long term corrosion test suggested that the nickel coating was able to effectively isolate the magnesium substrate from the solution. (Wei, et al., 2018) The combined spraying parameters from the reviewed studies are listed in Table 8.

***Table 8. Spraying parameters used for cold sprayed nickel coatings.***

| Parameter | Wei, et al., 2018 | Koivuluoto, et al., 2014 | Pontarollo, et al., 2011 |
|---|---|---|---|
| System | In-house made | KINETIKS 4000 | KINETIKS 3000 |
| Carrier gas | Nitrogen | Nitrogen | Nitrogen |
| Gas pressure (bar) | 25 | 38 | 30-40 |
| Gas temperature (°C) | 400 | 750 | 600-700 |
| Deposit material | Ni + AISI 410 | NiCu+Al2O | Inconel 625 |

Judging by the results found in litertature, cold spray can be used to form good quality barrier coatings using nickel alloys which can provide long term corrosion protection for component. This could allow cold spray to be used to both coat components and to repair damaged nickel plated components. As demonstrated by the Corrodkote test, either heat treating or blended powder should be used to archive the best corrosion protection. For new components with large coated areas it is probably beneficial to try to do without peening particles as their use increases the cost of the coating. For onsite repair use however the use of peening particles is probalby advisable to ensure good quality coating when possible lower gas pressures and gas temperatures are used, and heat treatment cannot be done.

### 4.3.3 Stainless Steel

This chapter reviews studies conducted on cold spraying stainless steels. The basic properties of stainless steels and their use in propeller fabrication are discussed in Chapter 4.1.2.

Adachi and Ueda studied the use of nitrogen carrier gas for cold spraying of stainless steel 316L using various gas temperatures and gas pressures. Not surprisingly a clear correlation with increasing coating quality can be seen, when either gas temperature or pressure is increased, with the maximum tested 35 bar gas pressure and 800 °C gas temperature providing the best results. Porosity of the resulting coating was 1.9 %. Adachi and Ueda also tested the hardness of each coating, which showed that either gas pressure or temperature had little effect on resulting hardness. (Adachi & Ueda , 2017) Figure 20 presents the microstructures of the coatings deposited using various gas temperatures and pressures.

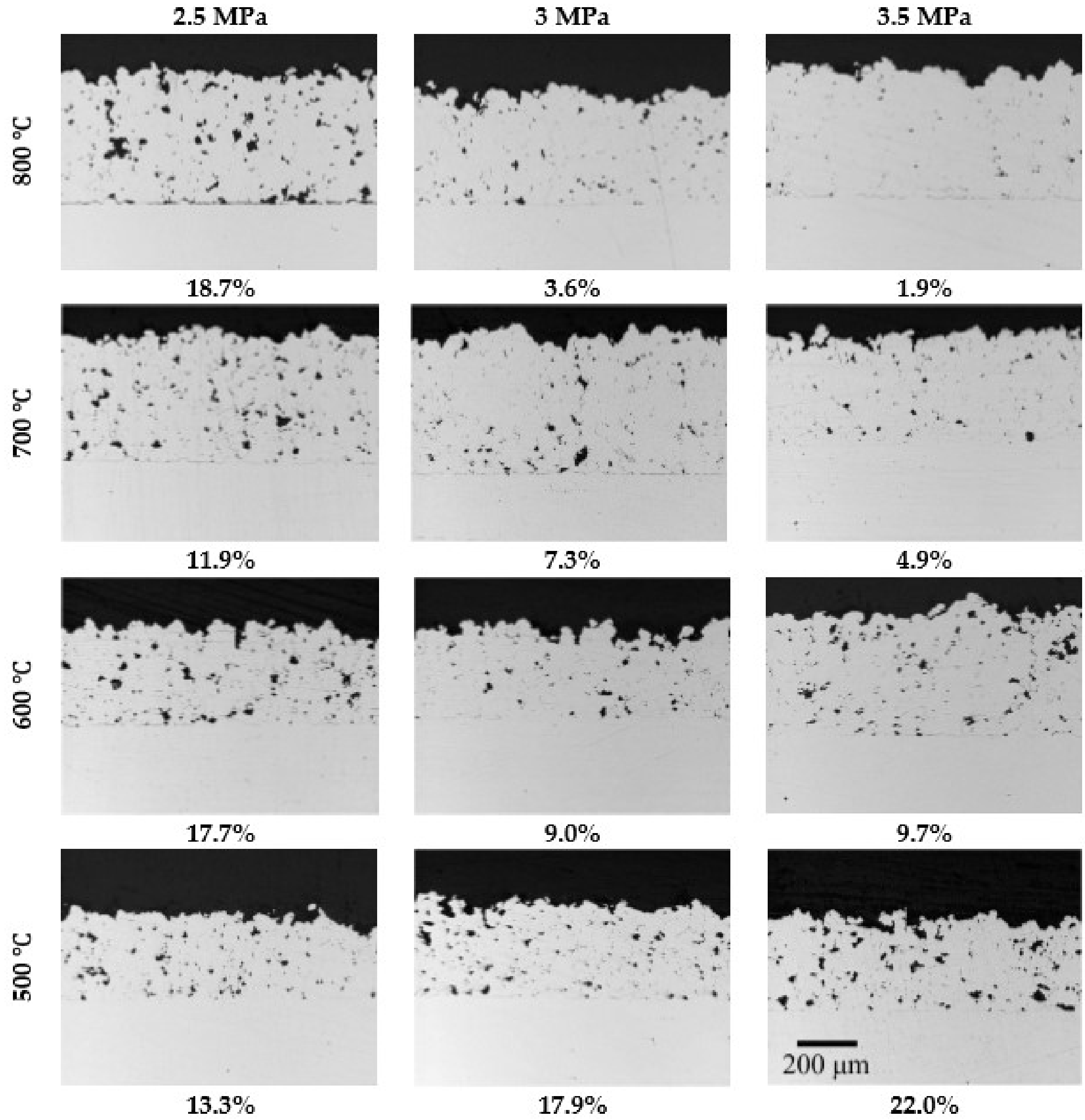


***Figure 20. Microstructure and porosity of cold sprayed AISI 316L coatings using various gas pressures and temperatures. (Adachi & Ueda , 2017)***

A study conducted by AL-Mangour et. al. on improving the strength and corrosion resistance of cold sprayed 316L stainless steel deposits. AL-Mangour et. al. coated mild steel substrates using different blends of 316L and cobalt alloy L605 powders and studied the microstructure, mechanical properties, and corrosion resistance in as sprayed and heat-treated condition. (AL-Mangour, et al., 2013) Figure 21 presents the microstructure of the blends heat treated at different temperatures. Both the 25 % and 33.3 % blends feature some porosity which could be removed with the heat treatment. 50 % percent Co alloy blend shows notable porosity even after heat treatment.

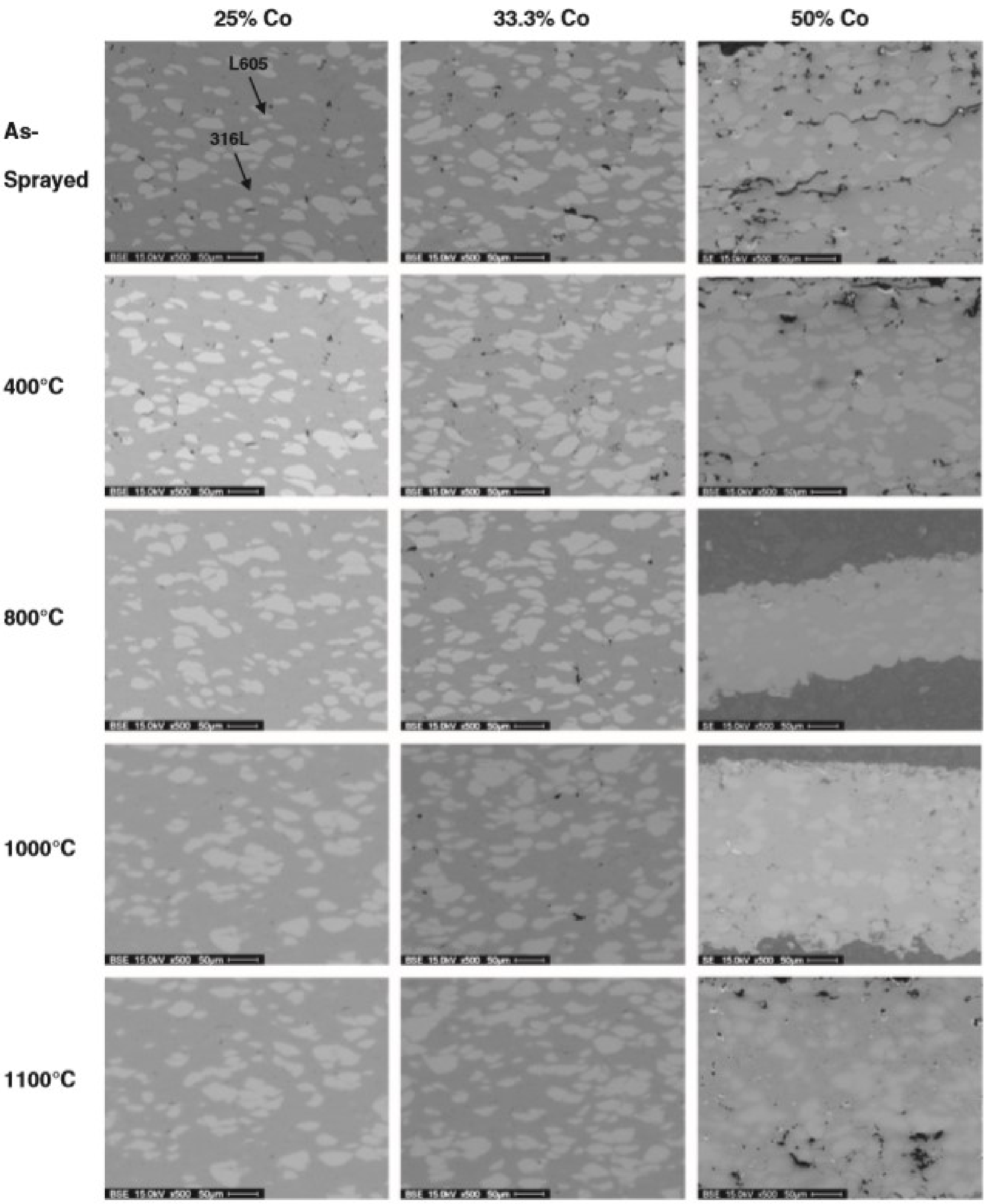


***Figure 21. Microstructure of the coating with different AISI 316L and Co alloy blends and annealing temperatures. (AL-Mangour, et al., 2013)***

Tensile strength and elongation of the coatings are presented in Figure 22. As expected, the as-sprayed coating presents little strength and elongation. Heat treatment at 800 °C already significantly increase the strength of the coating. Higher temperatures further increase the strength while also increasing the elongation, with heat treatment at 1100 °C giving excellent mechanical properties for the coating. It is worth mentioning that heat treating temperature of 1100 °C is very high and thus may be unpractical for production components.

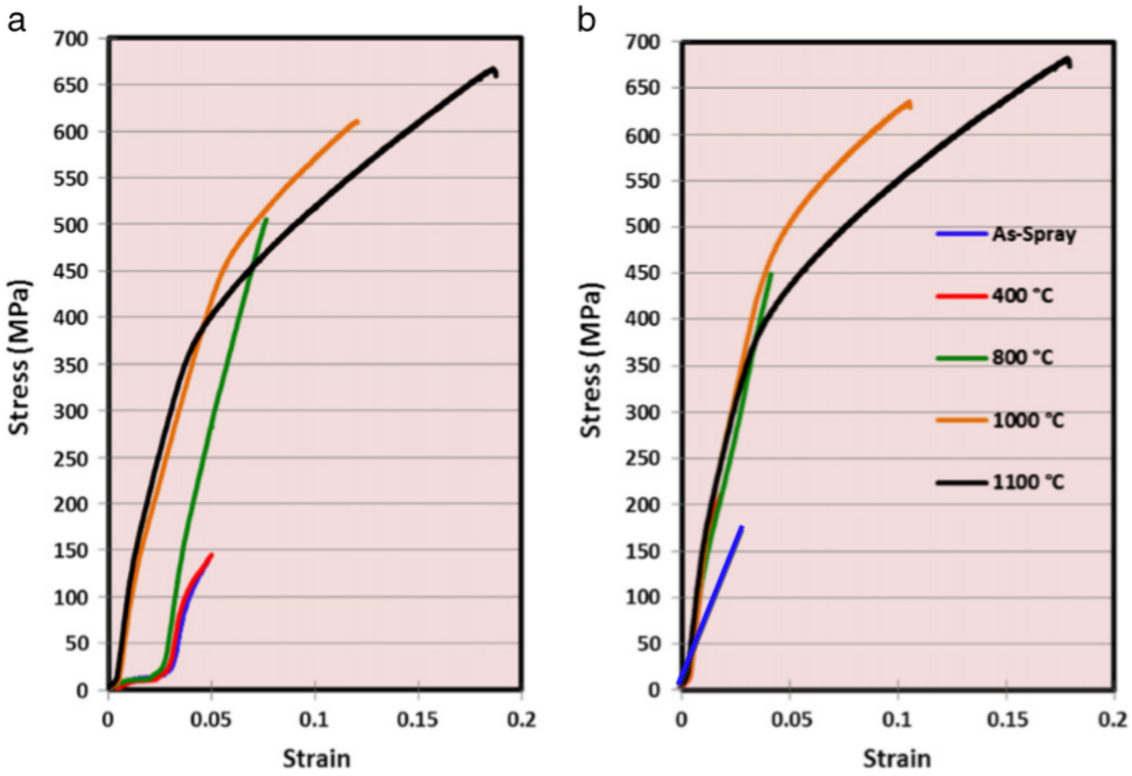


***Figure 22. Effect of heat treatment on the strength of the cold sprayed coatings. (a) 25% Co; (b) 33.3% Co deposited coating. (AL-Mangour, et al., 2013)***

The corrosion resistance of the deposits was analysed using potentio-dynamic polarization tests. The corrosion resistance of the as-sprayed coatings was found to be less than that of bulk material. Annealing increases the corrosion resistance to levels comparable to the bulk material, with the 25 % and 33.3 % Co blends showing better than bulk stainless-steel corrosion resistance. The corrosion rate of as sprayed stainless steel was 0.02 mm/year with the rate reducing to less than 0.005 mm/year with annealing.

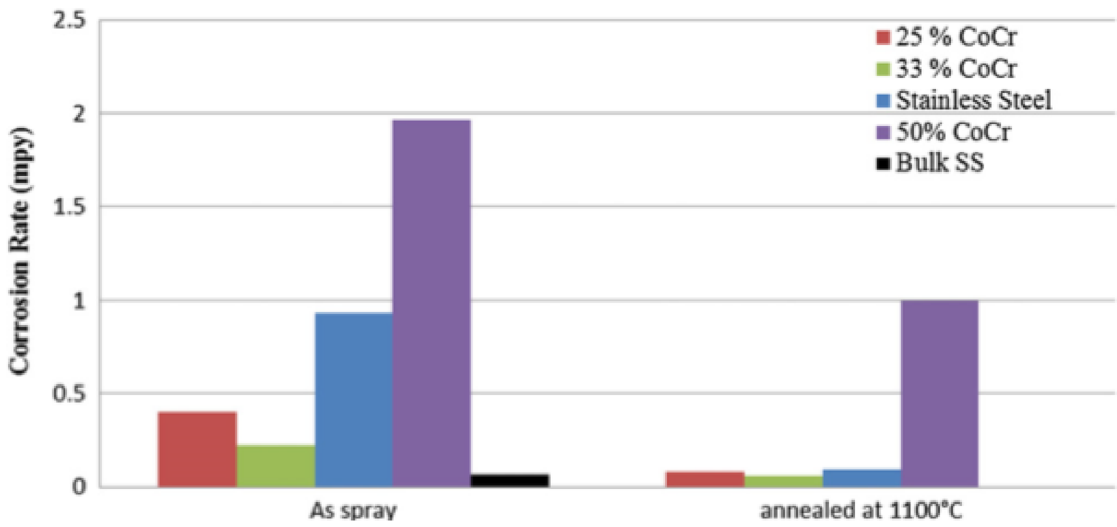


***Figure 23. Corrosion rate of the coating before and after annealing. (AL-Mangour, et al., 2013)***

Faccoli et al. studied the use of cold spray to demonstrate the repair of hydro turbine components made from martensitic stainless steels. The study compared two repair methods for the same damage: TIG welding and cold spray. Austenitic stainless steel AISI 316 was used for the cold sprayed repair as the material was deemed to be easier to spray than martensitic materials, while still providing the necessary material properties for the repair.

The study found that the hardness of the cold sprayed repair was higher than that of bulk material, which can improve the erosion resistance of the material. According to Faccoli et al. the method could be useful for repairing cavitation damage on hydroturbines, which operate in many ways in same conditions as marine propellers. The most important benefit of the cold sprayed repair over the welded repair is the lack of need for post welding heat treatment. (Faccoli, et al., 2014; Germanischer Lloyd Aktiengesellschaft, 2019) Figure 24 presents the cross section and microstructure of the simulated repair. Areas close to the cut cavity show high levels of porosity. The porosity decreases further away from the cut and on the areas which have been perpedicular to the spray nozzle.

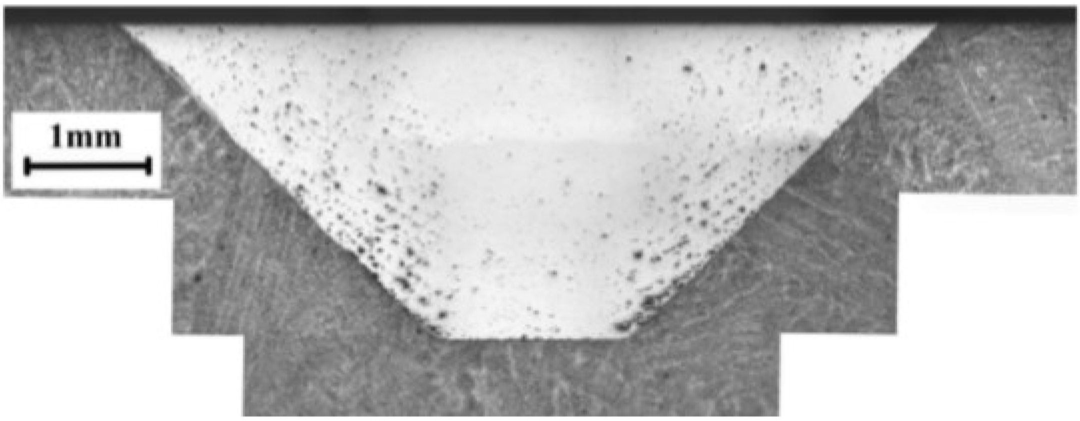


***Figure 24. Microstructure of repair on stainless steel sample done using cold spraying. (Faccoli, et al., 2014)***

Spray parameters from the presented studies are combined to Table 9. When comparing the parameters to the findings of the studies, it is clear that high gas pressures and temperatures are necessary for good quality deposits.

***Table 9. Parameters used to deposit stainless steel AISI 316L.***

| Parameter | Adachi & Ueda, 2017 | Faccoli, et al., 2014 | AL-Mangour, et al., 2013 |
|---|---|---|---|
| System | Kinetics 4000 | PCS-1000 | KINETIKS 4000 |
| Carrier gas | Nitrogen | Helium | Nitrogen |
| Gas pressure (bar) | 35 | 20 | 40 |
| Gas temperature (°C) | 800 | 1000 | 700 |
| Deposit material | AISI 316 | AISI 316 | AISI 316 + Cr |

Stainless steel is known to be a difficult material to deposit due to its tendency to work harden (or strain harden; note: use the term you want), with studies showing that some porosity remains in the coating even after using high process temperatures and pressures. Given the difficulty of depositing the material and the less than optimal corrosion resistance of the material, stainless steel is not an interesting material for corrosion protection of marine components. The studies suggest that adequate deposit properties can be archived to conduct non-structural repair on stainless steel components.

### 4.3.4 Nickel aluminium bronze

As discussed in previous chapters, nickel aluminium bronze is the most often used material for propeller manufacturing due to its good resistance to corrosion and cavitation while being relatively cost effective (Carlton, 2012). For the same reasons, the material is an interesting candidate for barrier coating and repair applications.

Bronze materials are both dense and ductile which causes them to be often simple materials to deposit using cold spray with both low- and high-pressure systems. (Koivuluoto, et al., 2012) Bronze materials with higher strength such as nickel aluminium bronze can be an exception to this as Krebs at al. have reported CuAl10Fe5Ni5 to be a challenging material to deposit due to the hard martensitic phases in the powder. Annealing of the powder removed the martensitic phase and improved the deformability of the powder which resulted in higher quality deposits. (Feng, et al., 2018; Krebs, 2016)

The use of different thermal sprayed bronze deposit for the repair of cavitation damage has been extensively studied by Krebs et al. The study shows that cold spray deposited nickel aluminium and manganese aluminium bronzes can have cavitation rates close to bulk nickel aluminium bronze if energy of the deposited particle is high enough. In the study η-value describes the thermal and kinetic energy of the sprayed particle, where η-value of 1 is the expected minimum value for bonding to substrate. Higher η-values describe increased particle energy, which is expected to increase the coating quality. Therefore, the η-value can be thought as a coating quality index. Figure 25 presents the microstructure and spraying parameters for various η-values.

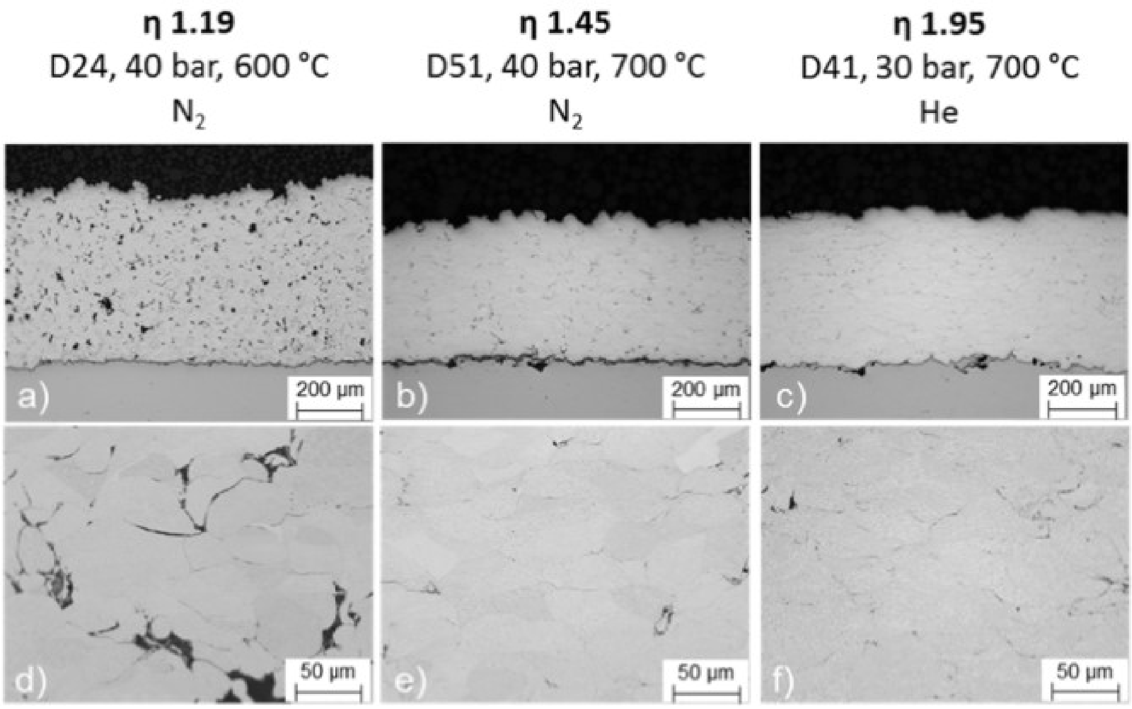


***Figure 25. Microstructure and spray parameters of cold sprayed deposit of annealed NAB powder on GL-A ship building steel. (Krebs, 2016)***

Figure 26 presents the cavitation rate of different bronze deposits with varying η-values or coating qualities. As can be expected, the coating quality has a great effect on the cavitation resistance of the coating.

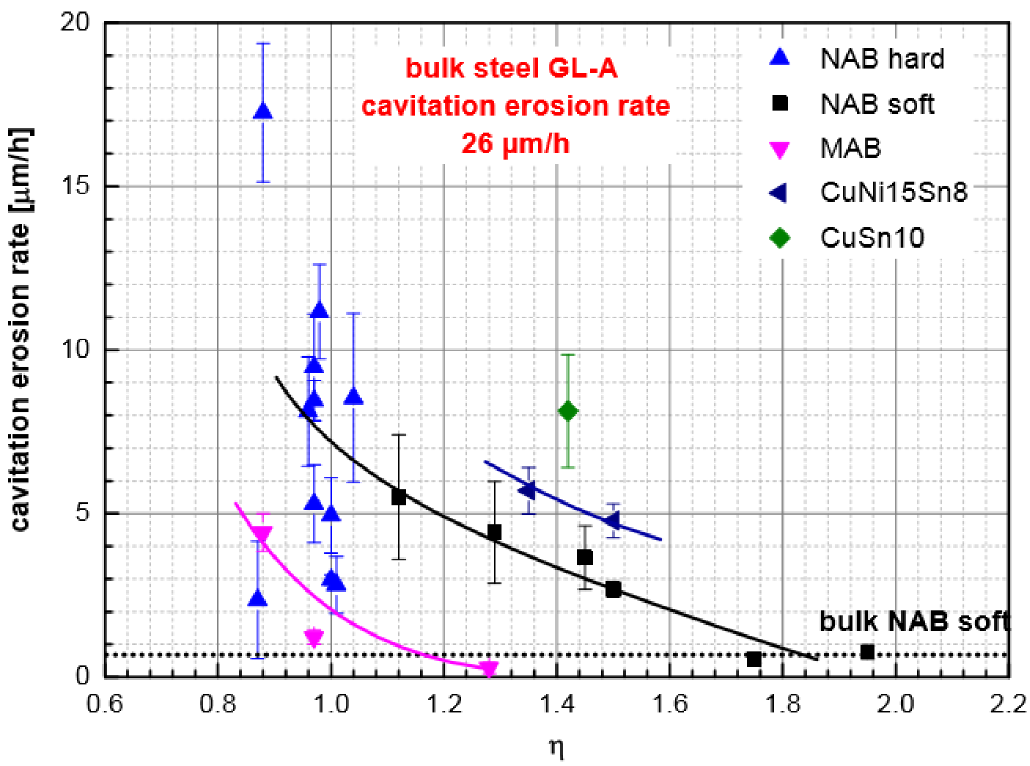


***Figure 26. Cavitation rate of different cold spray deposited bronze materials. (Krebs, 2016)***

Krebs reported that the coatings deposited using nitrogen carrier gas showed low cavitation rates, but the amount of loose non-bonded particles remained high. Cavitation quickly removed these particles which roughens the surface. (Krebs, et al., 2017) This may not be an issue in propeller repairs, as the surface is first filled with the deposit and then ground down to the wanted shape, as the deposit is often denser further from the surface. (Koivuluoto, et al., 2012) Krebs also studied the effects of post spray heat treatment on the cavitation rates. Annealed powder was found to have better cavitation resistance even before post spray heat treatment when compared to the non-annealed powder. Figure 27 presents the cavitation erosion rate of the coating after heat treatment.

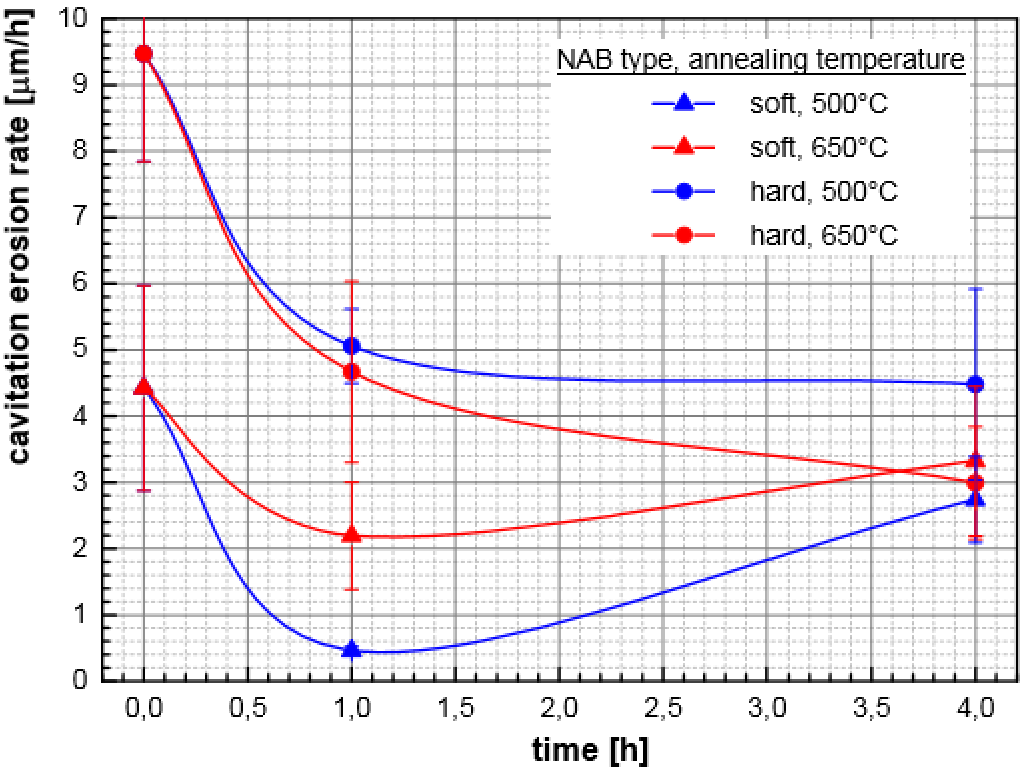


***Figure 27. Effect of heat treatment on the cavitation rate of CS deposited NAB. (Krebs, 2016)***

Ultimate tensile strengths of the NAB deposits after different heat treatments can be seen in Figure 28. As can be seen, a one-hour heat treatment significantly improves the strength of the deposit. Longer heat treatment does not have much effect on the strength but as with other materials the elongation most likely is improved. Again, better performance is attained by using the annealed powder.

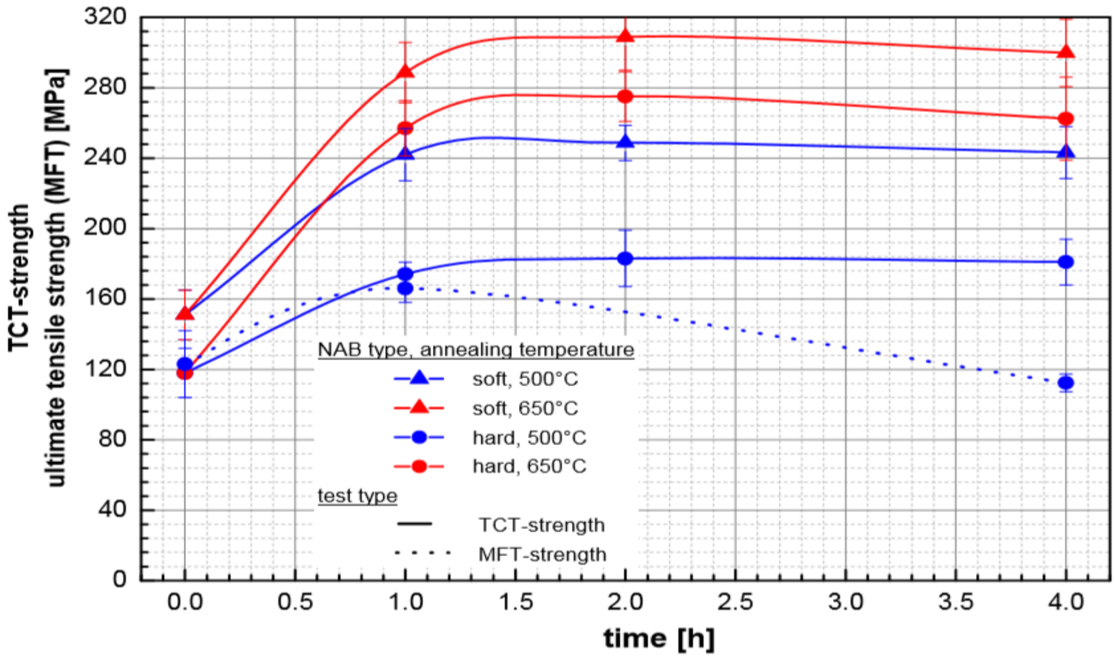


***Figure 28. Ultimate tensile strength of NAB coating in respect to post spray heat treatment. (Krebs, 2016)***

According to Krebs cold spray, warm spray and HVOF can be used to successfully deposit dense coatings with good mechanical properties and cavitation resistance if spray parameters are selected so that high particle velocities and temperatures are attained. Otherwise post spray heat treatment can be used to improve the coating quality if optimal spray parameters cannot be used, but this increases the overall cost and complexity of the manufacturing process. (Krebs, 2016) Table 10 presents satisfactory spray parameters for nickel aluminium bronze based on the results from Krebs.

**Table 10. Satisfactory parameters for NAB repair using cold spray.**

| Parameter | Value |
|---|---|
| Carrier gas | Nitrogen |
| Gas pressure (bar) | 40 |
| Gas temperature (°C) | 700 |
| Deposit material | Annealed CuAl10Fe5Ni5 |

Nickel aluminium bronze can be deposited using cold spray and other thermal spray methods to form cavitation resistant deposit with good mechanical properties, which allows the material and process to be used for non-structural repairs and cavitation resistant coatings. These properties can be further improved by heat treating. Study conducted by Krebs shows that nickel aluminium bronze powder should be in annealed condition to archive good results. Annealing removes hard martensitic phases from the powder which improves the adhesion of the deposit material.

## 4.4 Conclusion: coating materials

Titanium has excellent corrosion resistance and mechanical properties, but due to its low density and high strength, archiving dense coatings is difficult even when using high pressure cold spray systems. Through pores compromise the barrier function of the coating which can lead to failure of the coating and the part. Laser assisted cold spray processes have been used to successfully form dense coatings in titanium, but such technology is not yet commercially available.

Nickel alloys have excellent corrosion resistance and good mechanical properties. These materials are dense and ductile which allows them to be sprayed with ease using high pressure cold spray systems. Nickel alloys are also sprayable by low pressure systems which is important characteristic for repairability of the coatings. Literature shows many examples of successful deposition of dense coatings using nickel alloys, which combined with the good corrosion resistance makes it a good candidate for corrosion resistant barrier coating. Even still the real-world performance of cold sprayed nickel barrier coatings on large parts is unknown and needs to be tested before any practical use.

Many examples of successful stainless-steel coatings were found in literature. The material has worse corrosion and cavitation resistant properties than the other discussed materials. The material is also difficult to deposit using cold spray, so the material is not ideal for protective coatings. The material could however be used to do non-structural spot repairs on stainless steel components. In these cases, the cold spray process would provide benefit over competing welding repair as no post repair heat treatment is required.

Bronze has good resistance to corrosion and cavitation erosion. It is dense and ductile and can be deposited by both high- and low-pressure systems. This allows bronze to be used to repair damage on propellers manufactured from nickel aluminium bronze. Bronze materials are effective in preventing accumulation of biological fouling which promotes long term efficiency of the propeller.

# 5. COLD SPRAYING

Cold spray process was accidentally invented in former Soviet Union in 1980's, while studying material abrasion using high velocity particle spray. It was found that if abrasive media was accelerated to high enough velocity, it deposited to the surface of the substrate instead of cutting it (Papyrin, et al., 2006). Nowadays cold spray process is being used apply coatings, repair parts, and produce near net shape for manufacturing. (Titomic, 2020; Fauchais, et al., 2014)

## 5.1 Operating Principle

Cold spray is a process in which material particles are accelerated to supersonic velocities using compressed gas. The process is termed cold spray as the particles are sprayed at or near-room temperature, which distinct it from other thermal spray methods that relay on heat in addition to the particle velocity. ( Fauchais, et al., 2014, p. 33) Schematics of basic cold spray system can be seen in Figure 29.

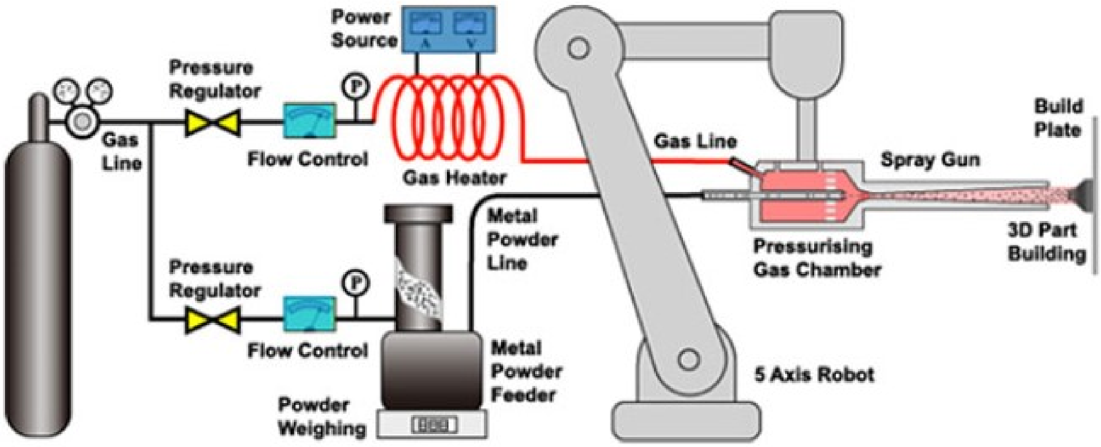


***Figure 29. Schematics of cold spray system. (Titomic, 2020)***

Cold spray process is divided to high- and low-pressure processes. The difference between them is in the pressure of the carrier gas, and thus in the velocity of the sprayed particles. In high pressure process the carrier gas accelerates the particles to sufficiently high velocity to form a bond between the particle and the substrate material. Particle velocities attained by the low pressure process are not high enough to deposit a coating by itself, so the process relays on the use of powder mix which is blended with harder particles, the purpose of which is to shot peen the actual coating material to the substrate. ( Fauchais, et al., 2014, pp. 33-34)

Thermal sprayed coatings are often evaluated by their adhesion strength, density, and level of oxidation. (Villafuerte, 2015, p. 8). Cold spray process often has better adhesion and density of coating when compared to other thermal spraying methods as a result of the lower particle temperature, which is not sufficiently high to promote oxidation off the particles, thus promoting metal to metal bonding. High particle velocity results in high deformation of the particles which together with the shot peening effect of the spray results in denser coatings than those archived with other thermal spray methods. Comparison of coating material microstructure with different spray methods is presented in Figure 30.

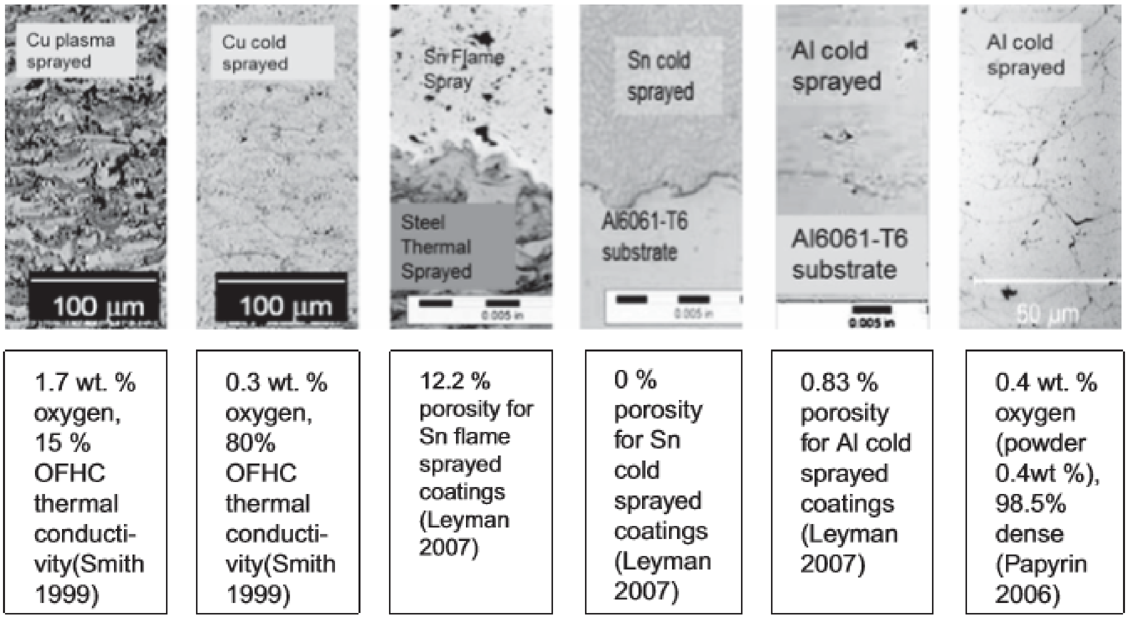


***Figure 30. Comparison of material microstructure between thermal spray methods. (Villafuerte, 2015)***

When compared to other thermal spray processes, HVOF process is the closes competing process for cold spray, as it can also produce deposits with low porosity and good mechanical properties. When compared to HVOF the main advantage of cold spray is its better energy efficiency, deposits have lower oxidation and no requirement to use and handle explosive gases. ( Fauchais, et al., 2014)

Main drawbacks of cold spray process are its high consumption of carrier gas and the brittle nature of the coatings due to the high plastic deformation caused by the coating process. Post spraying heat treatment is often employed to remove tensile stresses and to improve ductility and strength of the deposits. (Villafuerte, 2015)

## 5.2 Cold Spray Equipment

Cold spray systems are available in many different forms each of them having their distinctive advantages and limitations. ( Fauchais, et al., 2014, pp. 33-34)  Low pressures systems often use compressed air as the carrier gas which limits the deposit materials to ones with low critical velocity, such as zinc, tin, nickel, copper, and aluminium. To aid deposition the powder is often mixed with a percentage of harder ceramic particles which hammer the surface and help form the deposit ( Fauchais, et al., 2014, pp. 33-34). Low pressure is often portable and thus a good solution for onsite applications and repair uses when only soft materials are being deposited. The low-pressure equipment is also a magnitude cheaper to acquire than a high-pressure system due to the reduced size and complexity of the system  (Assadi, et al., 2016). Deposition efficiency and rate of low-pressure systems is small when compared to high pressure systems. Dymet 423 is an example of portable low-pressure cold spray system. It features deposition efficiency of 20-30% with the deposition rate is 3-10 g/min depending on the material. Dymet 423 is presented in Figure 31. (Dycomet Europe, 2020; Villafuerte, 2015; Fauchais, et al., 2014)


***Figure 31. Portable high-pressure cold spray system (left) and a portable low pressure cs system (right). (VRC Metal Systems, 2020) (Dycomet Europe, 2020)***

High pressure systems are used when better mechanical properties, higher deposition rates or harder deposit materials such as steels or titanium are deposited. High pressure systems use nitrogen or helium as the carrier gas and operate at higher pressure levels to archive higher particle velocity than low pressure systems. (Villafuerte, 2015; Fauchais, et al., 2014) High pressure systems are available in both portable and fixed installation forms, although it must be noted that the portable high-pressure system is significantly larger and more complex than portable low-pressure system as can be determined by comparing a portable high-pressure cold spray system from VRC metal systems to a Dymet 423 low pressure system in Figure 31.

Both low- and high-pressure systems can be handled manually to deposit material locally but for more sophisticated applications either the spray gun or the substrate can be mounted to computer-controlled manipulator such as robotic arm. Such setups are necessary for archiving coatings with tight tolerances, for coatings of large areas and for additive manufacturing uses. (Villafuerte, 2015, pp. 263-264) While many designs for complete spray systems are available from different manufactures, often a completely custom spray setup needs to be constructed for the required application. Such cases may occur when the spray system in integrated as part of a production process or the part has characteristics that necessitate a custom system to be build. (Villafuerte, 2015, pp. 270-273) Figure 32 features a robotic manipulated high-pressure spray system by Titomic. The setup is quite representative of which a setup to coat individual propeller blades might look like.

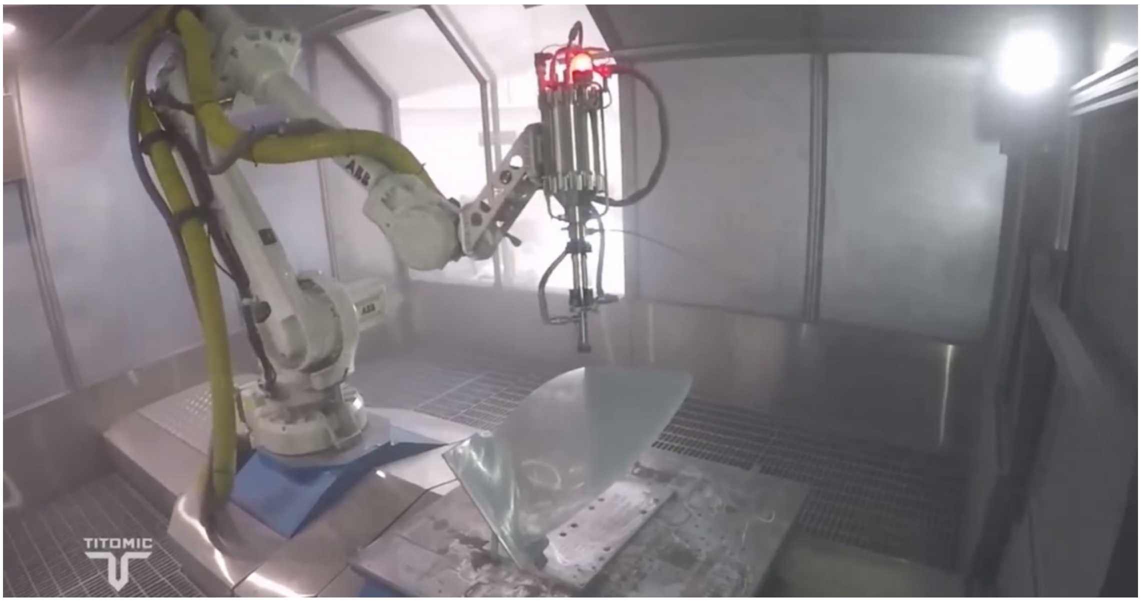


***Figure 32. Titomic cold spray system coating a blade like component. (Titomic, 2020)***

Table 11 contains basic information about some of the commercially available cold spray systems. The publicly available specifications of the systems have been converted to common units for easier comparison. For volume-based deposit rates, the density of nickel 8.91 kg/l has been used to attain comparable grams per minute deposit rates.

***Table 11. Commercially available cold spray systems.***

| Make | Model | Type | Max pressure (bar) | Max temperature (°C) | Deposit rate |
|---|---|---|---|---|---|
| Dymet | DYMET 423 | Portable LPCS | 8 | 600 | 50 (g/min) |
| Plasma Giken | PCS-H10 | Portable HPCS | 30 | 800 | N/A |
| VRC metal systems | VRC GEN III | Portable HPCS | 70 | 650 | 100 (g/min) |
| Plasma Giken | PCS-1000 | HPCS | 75 | 1100 | 300 (g/min) |
| Plasma Giken | PCS-100 | HPCS | 75 | 1100 | 100 (g/min) |
| Impact innovation | Impact spray system 5/8 | HPCS | 50 | 800 | 230 (g/min) |
| Impact innovation | Impact spray system 5/11 | HPCS | 50 | 1100 | 230 (g/min) |

Efficient coating of large propellers requires special coating system to be build and the process optimized for reliable results. To archive this, it is important to discuss the project with cold spray equipment manufacturers and powder suppliers to find the appropriate equipment, process parameters and materials. It is also worth noting that due to the large coating volume, large coated area and thin coating thickness, fast travel speeds are required. The fast travel speeds and high accelerations combined with the weight of the spray gun can have a detrimental effect on the accuracy of the spray gun manipulator.

## 5.3 Coating Adhesion Strength

In cold spray the material bonding mechanism is a mixture of mechanical trapping and metal to metal bonding depending on the material combination and spray parameters. Metal to metal bonding is attributed to adiabatic shear instabilities similarly to in explosion welding. Quick deformation of the particle breaks the oxide layers between the particle and the substrate thus allowing metal to metal contact to occur. High pressure and material flow velocity from the impact force the materials to intimate contact and forms metal to metal bond. (Walker, 2018; Villafuerte, 2015) Figure 33 demonstrates the effects of particle to substrate impact between different material pairs. The material flow increases further from the centre of the contact point. Thus, it is estimated that the metal to metal only occurs on the outer edges of the splat. Soft materials with low melting point have presented inter-facial melting and generation of intermetallic phases at the interface. (Walker, 2018; Villafuerte, 2015) Generally, the adhesion strength of the coating improves with increased particle velocity and higher preheating temperatures.

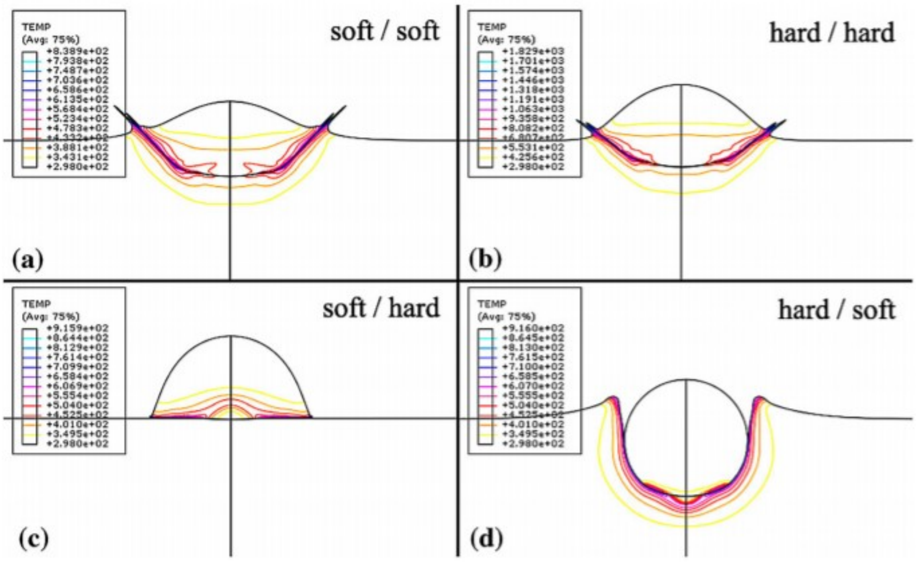


*Figure 33. Deformation and temperature on four cases: a) Al on Al at 775 m/s, b) Ti on Ti at 865 m/s, c) Al on mild steel at 356 m/s, d) Ti on Al at 655 m/s. (Walker, 2018)*

Adhesion strength values for various cold sprayed coatings are presented in Table 12. Post spray heat treatment can in some cases be used to improve the adhesion strength of the coating.

*Table 12 Adhesion strength of various substrate and deposit material combinations.*

| Substrate | Deposit | Reference | Parameters | Adhesion strenght (MPa) |
|---|---|---|---|---|
| Steel S235 | Ni-Al-bronze | Krebs, 2016 | Carrier gas: Ni<br>Pressure: 40 Bar<br>Temperature: 700°C | 45 |
| Al 6061 | Co | Hussain, et al., 2008 | Carrier gas: He<br>Pressure: 29 Bar<br>Temperature: 20°C<br>Grit-blasted surface<br>HT: 450°C, 1h | (As sprayed) 35.5<br>(Annealed) 56.6 |
| Mg AZ31B | Ni (mixed with 30 | Wei, et al., 2018 | Carrier gas: Ni<br>Pressure: 25 Bar<br>Grit-blasted surface<br>Temperature: 400°C<br>Shot peen assisted spraying | >65.4 (Glue failure) |

Spraying can form either tensile or compressive residual stresses to the coating. Tensile stresses are formed by difference in temperature and the thermal expansion between the materials. Alternatively, compressive residual stresses can be formed if the shot peening effect of the coating process is dominant. Residual tensile stress can lead to problems with low bonding and cracked coating. (Villafuerte, 2015, pp. 225-253)

## 5.4 Cold Spray in Manufacturing

As with any manufacturing method, the successful application of cold spray requires both the part and the process to be designed and conducted appropriately. This chapter gives basic guidelines to the part design, spray preparation and post processing for thermal spray and cold spray applications.

### 5.4.1 Part Design

Part should be designed so that it does not promote the damage and delamination of the coating. To prevent cracking and delamination the part should be designed so that the coating does not end abruptly but instead the thickness of the coating is gradually decreased to be level with the substrate. Alternatively, a recess can be machined for the coating. Sharp edges on the coating can lead to development of cracks, from which the coating will start to peel off and separate from the substrate. ( Fauchais, et al., 2014, p. 756) Figure 34 illustrated some best practices that apply to designing parts for thermal spray coatings.

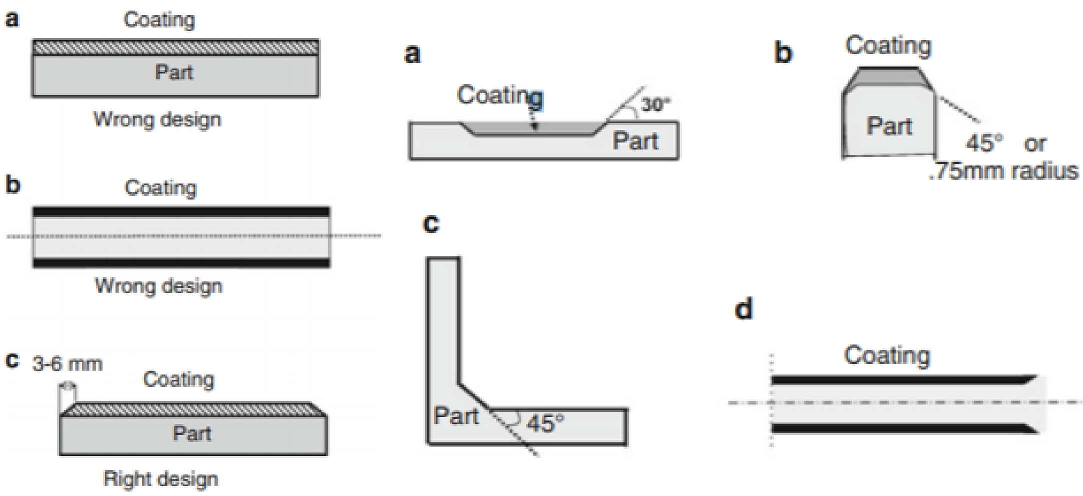


***Figure 34. Correct shaping of the coating and the base part.***

Machining can also be used to create grooves to the base material prior to roughening the material surface. The machined grooves are used to transfer the shear stresses from the base material to the sprayed material, thus the direction of the grooves must be chosen correctly in relation to the stresses acting on the sprayed part. The grooves are used mainly when spraying thick coatings. The representation of the grooved and smooth substrates are presented in Figure 35. ( Fauchais, et al., 2014, p. 757)

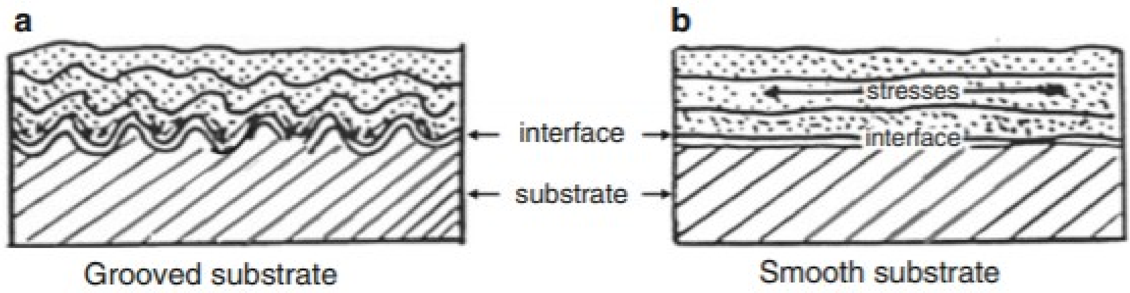


***Figure 35. Shear stress transfer between the deposit and substrate for grooved and smooth substrate. ( Fauchais, et al., 2014, p. 757)***

Many applications feature mechanical and thermal loading of the part. In these cases, it is important to consider the behaviour of the substrate and deposit under these varying conditions. Loading of the part leads to deformations in the part. As the deposit material often has differing Young's modulus or thermal expansion coefficient to the substrate material, shear stresses occur at the interface of the materials when the part is deformed which can lead to cracking or delamination of the coating.

### 5.4.2 Cleaning and Roughening

Cleaning and roughening are the first steps of preparing the substrate for spraying. Cleaning is done to remove contaminants such as grease, oil and paint and mill scale which can prevent the deposit from properly adhering to the substrate. ( Fauchais, et al., 2014, p. 757) The cleaning can be done using solvents and abrasive medium to remove the contamination. Prior to cleaning sand cast parts should be oven baked at temperature of 315 °C for four hours to remove all oil from the pores of the part. ( Fauchais, et al., 2014, p. 758)

After cleaning, the surface of the part must be roughened to create good bonding surface for the sprayed material. Dry abrasive grit blasting such as sand blasting is commonly used for roughing ( Fauchais, et al., 2014, p. 758). The used grit size must be chosen according to the sprayed material and other spraying parameters as the surface roughness left by the grit influences how the sprayed material deforms over the surface peaks of the substrate, and thus affecting how well the sprayed material can adhere to the substrate. Further cleaning of the part is necessary after grit blasting to remove any loose particles and embedded grit material which could compromise the coating adhesion. ( Fauchais, et al., 2014, p. 779)

In cold spray process the high velocity particles blast the surface which roughens the surface and activates the substrate surface. For this reason, grit blasting is not necessary for cold spray process. It has been observed that with cold spray polished surface often results in better bonding between the coating and the substrate. (Villafuerte, 2015, p. 53)

### 5.4.3 Masking

Masking is done to prevent the spray depositing on unwanted surfaces of the part. According to Fauchais et al. the masking process is chosen based on the quantity of the sprayed parts. For small production runs the masking process can be done using masking tape, while for larger production runs the masking can be done using permanent masking which can be used for multiple parts. In addition, the masking process using permanent masks can be automated as part of the automatic spraying process. ( Fauchais, et al., 2014, p. 760) As per the guidelines stated in Chapter 5.4.1 the masking must be done so that sharp edges are not created.

### 5.4.4 Post spray heat treatment

Due to the nature of the cold spray process the sprayed deposit undergoes a large degree of plastic deformation. This causes the deposit to be hard and brittle. A post spray heat treatment can be employed improve the improve the properties of the coating. The heat treatment promotes diffusion, recrystallization, and grain growth in the material, which closes the interparticle interfaces and reduces the porosity of the coating. (Sun, et al., 2020) The practical benefits from heat treating include improved mechanical properties and bonding, increased coating quality and increased corrosion resistance. (Sun, et al., 2020) The true archived effect of the heat treatment is obviously dependant on the deposit material, part design and on the used spray parameters but with all else being equal: increase in the heat treating temperature and time increases the elongation and to a degree the strength of the material while reducing porosity within the deposit.

The required heat treating temperature is related to the melting point of the material with higher melting point requiring higher heat treating temperature. The heat treating can be done using a furnace, laser, or eddy current heating. Vacuum or inert gas atmosphere is utilized when the heat-treating temperature is high and there is a need to limit the oxidization of the material. Table 13 presents various heat treatments and their effects on selected materials. The table is adapted from work done by Sun, et al.

***Table 13. Various heat treatments and their effect on the material. Adapted from (Sun, et al., 2020)***

| Coating | References | HT Parameters | Main Finding |
|---|---|---|---|
| SS316L | Yin, et al., 2019 | Temperature: 1000 ◦C<br>Duration: 4–8 h<br>Atmosphere: Air, vacuum | Enhanced mechanical properties of the coatings were mainly dominated by improved inter-particle bonding and particle grain structure rather than reduction of porosity. Air annealing only slightly improved the tensile strength and ductility of the SS316L deposits. Vacuum annealing significantly improved the tensile strength and ductility of the SS613L deposits. |
| IN718 | Ma, et al., 2019 | Temperature: 990 ◦C<br>Duration: 4 h<br>Atmosphere: Ar | A high-performance of the coatings after HT was achieved with the adhesive strength between coatings and substrates being comparable with the tensile strength of the bulk materials after HT. |
| Al | Spencer & Zhang, 2009 | Temperature: 400 ◦C<br>Duration: 20 h<br>Atmosphere: Ar | An Al3Mg2 or Mg17Al12 intermetallic compound layer was formed at the coating/substrate interface, which was significantly harder than the aged AZ91 alloy and offered a corrosion resistance similar to that of the Al alloys. |
| Cu | Sudharshan, et al., 2007 | Temperature: 300 ◦C<br>Duration: 1 h<br>Atmosphere: vacuum, air | The electrical conductivity of the coatings after HT was comparable to bulk materials. Vacuum condition during HT yielded lower porosity and higher conductivity of the coatings. |

While heat treatment certainly can improve the coating quality, it is an extra step which increases the cost, and complexity of the propeller coating process. For this reason, it is likely beneficial to try and optimize the spraying parameters to limit the need for post spray heat treatment.

### 5.4.5 Machining

Machining, sanding, or grinding of the cold sprayed deposit is often necessary to archive the wanted shape and surface finish on the part. This chapter discusses the machining characteristics of cold sprayed deposits. (Moog Aircraft Group, 2018; Yin, et al., 2018; Honeywell, 2017; Champagne & Helfritch, 2014) Depending on the material, spray parameters and post processing the machinability of the material is described to be like machining the material in either bulk or sintered form. In the bulk form the material is removed by the shearing action of the cutting tool, while in the sintered form the material is removed by the dislodging of particles instead of cutting. The differences between the two cutting actions are described in Figure 36. (Aldwell, et al., 2017)

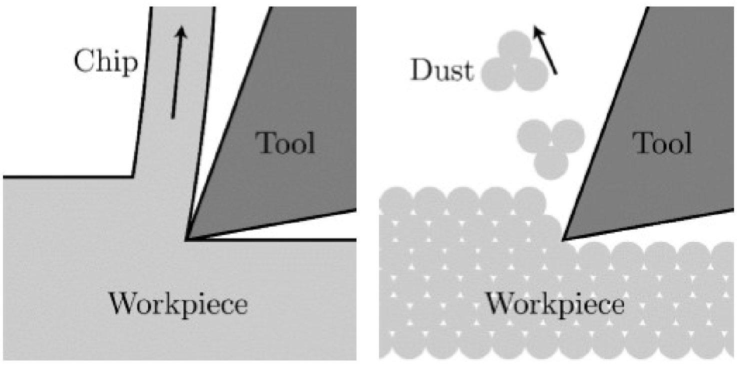


***Figure 36. Material removal of fully dense and a material with weak particle bonds.***

According to Aldwell et al. materials with poor bonds between particles tend to produce poor surface finish as the material is removed by dislodging and then smearing across the cut surface. Machining characteristics of deposit with good interparticle bonding and low porosity is reported to be similar to the bulk material. (Aldwell, et al., 2017) Overall few studies about machining of cold sprayed deposits were found. Machining is mentioned as a common part of a process in multiple studies indicating that, in general machining of the deposit is not an issue.

## 5.5 Economics of Cold Spray

This chapter discusses the estimation of costs associated with cold spray process. Accurate estimation of the costs associated with the cold spray process is important for assessing the methods potential in production use. The manufacturing costs can be divided in direct and indirect costs. Direct costs include all costs that are directly related to the production steps such as material consumption and labour. Indirect costs or overhead costs mainly consist of investment related costs, plant maintenance, rents and other costs which remain constant regardless of the production rate. under three categories: material cost, labour costs, and overhead costs. ( Fauchais, et al., 2014, p. 1514) In cold spray process the material costs are carrier gas and the deposit powder. The preparation, setup and finishing of the spraying process and the sprayed part require manual labour, which is the direct labour cost of the process, while machine maintenance, depreciation, and other utilities costs of the spraying equipment represent the overhead costs. (Villafuerte, 2015; Fauchais, et al., 2014)

### 5.5.1 Material costs

Material costs are based on the deposited mass and material price. The deposited volume can be easily calculated from the physical size of the sprayed area, thickness of the coating and the deposition efficiency of the spraying setup. Thus, the powder usage can be estimated by dividing the mass of the coating and overspray with the deposit efficiency of the spraying equipment. (Villafuerte, 2015, p. 378) The mass of used carrier gas can be calculated by employing a known mass to gas ratio which is often around 0.05, so approximate mass of used gas is 20 times higher than that of used powder. (Villafuerte, 2015, p. 378)

### 5.5.2 Labour

Calculation of labour costs depends on if the worker is paid only for the time spent on given activity or if he is paid regardless of his activity. Prior case is used in subcontracting where a given labour rate is billed from the customer based on the used labour time, while in the latter case the labour costs are part of fixed overhead costs which are applied to a project accordingly. (Villafuerte, 2015, p. 379) For this analysis, a constant hourly rate for labour is assumed for simplicity.

Labour costs can be attained by multiplying the known before, during and after spray labour times with appliable labour rates. The before spray labour may consist of planning, fixture manufacturing, robot programming, testing, and part loading. During spray, the machine may need to be observed and operated depending on the process. After the spray, the part needs to be unloaded from the spray system, fettled, and transported. (Villafuerte, 2015, p. 379) Time required for the said procedures is highly dependent on the project and on the skill and experience of the workers, so estimating the time consumption beforehand can be difficult.

### 5.5.3 Overhead

Overhead costs can be categorized on two categories: variable and fixed overhead cost. Variable overhead consists of costs that come from the production process and thus vary in relation to the production volume. Fixed overhead describes costs that are constant in relation to the production volume. Examples of such cost are rent of the production facilities and depreciation of equipment. Main variable overhead cost associated with the cold spray process is electricity. Electricity is used to heat the carrier gas, provide motion for the spraying robot and power other equipment such as the control computer, lighting, and ventilation. (Villafuerte, 2015, p. 379) The energy needed to heat the gas can easily calculated when the mass of the used gas and the temperature difference before and after the heating is known. Little electricity is used by the other systems when compare to the heating of the gas. Thus, the other systems can be safely excluded from the costs analysis. The overhead costs are used to calculate an appropriate hourly rate for a given production machine. The time required to spray a single part can be estimated with adequate accuracy when the deposition rate of the spraying equipment is compared to material needed to spray the part (Villafuerte, 2015, p. 379).

### 5.5.4 Total Cost

This chapter discusses the estimation of total coating costs using a MATLAB script, which calculates the total cost as a function of propeller size. Example propeller used in this analysis is one of ARC 1.2 thruster. The original propeller has a diameter of 4.8 m and a weight of approximately 27 tons. The total surface area of single ARC 1.2 propeller blade is 10.63 $m^2$. The proposed coating is a 0.3mm thick layer of Monel 400. Density of Monel 400 is 8800 $kg/m^3$. Weight of one square meter of coating with thickness of 0.3 mm is calculated to be 2.64 kg. From this information the total weight of the coating for all blades is determined to be around 112 kg, while the total coating volume is 0.0128 $m^3$. Illustration of ARC 1.2 propeller can be seen in Figure 37. The used coating thickness value of 0.3mm is based on the thickness of barrier coatings found in literature. As propellers are expected to operate for a long time in a hostile marine environment the practical coating thickness may vary significantly.

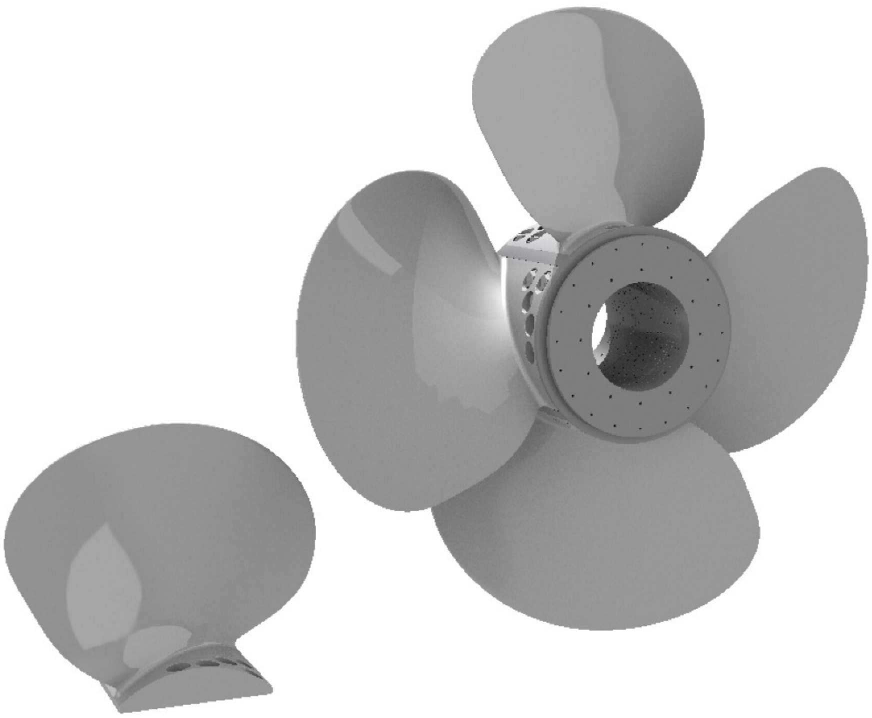

***Figure 37. ARC 1.2 Propeller and single blade.***

To analyse the costs and the costs structure of the coating process a MATLAB script was done. The example propeller was scaled to multiple different sizes ranging from 1 meter to up to 10 meters in diameter. Surface area for single propeller blade was calculated for each propeller size using a CAD software. The surface area data was imported to MATLAB and a function describing the blade area as a function of propeller diameter was formed. The blade area function can accurately describe the coated area of a four-blade propeller with a similar shape to the ARC 1.2 propeller blade. For this early stage feasibility analysis, the same area function is used to describe all analysed use cases. For more accurate analysis it would be beneficial to form individual area function for other propeller types, with different blade counts and geometries, to eliminate any errors in required coating volume.

As discussed in Chapter 5.5, the total cost can be calculated when material costs, labour costs and overhead costs are known. Material consumption was estimated from the surface area, coating thickness, deposit efficiency and overspray coefficient as described by Villafuerte. Gas consumption was then calculated from the gas to powder ratio of 20:1 Electricity costs are calculated from the energy needed to heat the used gas mass to required temperature. (Villafuerte, 2015)

Overhead costs and machine time were estimated from the now known deposit mass and from estimated deposition efficiency and deposit rate. European vendor for Plasma Giken: Dycomet Europe B.V estimated the maximum appropriate deposit rate to be 400 grams per minute for nickel alloys when using the PCS 1000 system. By using an estimated deposition efficiency of 0.9 the deposited mass per hour can be calculated to be 21.6 kg/h. Using this information, the time spraying can be estimated to be around 5.2 hours for 4.2 m propeller if the spray system can operate without stoppages.

Total labour times were estimated by estimating the programming, setup, and parts handling times. Set up time per part consists of loading the part to the fixture, preparing the spraying equipment, and again removing the part after spraying. Larger parts are naturally more difficult to handle, but the actual sensitivity to propeller size might be small as both small and large propellers require the same heavy equipment for handling. Before spraying preparations consists of fabricating the needed fixtures and tooling and from programming the spray path. Time required for both actions can be assumed to be relatively constant regardless of the size or type of the propeller. Without any empirical data the times used for labour cost estimates are subjected to significant uncertainty. All parameters used in the analysis can be found in Table 14.

***Table 14. Calculation parameters.***

| Parameter | Value |
|---|---|
| Deposit material | Monel |
| Deposit material density | 8800 kg/m3 |
| Carrier gas | Nitrogen |
| Carrier gas cp | 1.05 kJ/kg*K |
| Powder price | 100 €/kg |
| Carrier gas price | 0.14 €/kg |
| Electricity price | 0.15 €/kWh |
| Labour price | 75 €/h |
| Deposit rate | 400 g/min |
| Machine rate | 500 €/h |
| Pre spray setup | 20h |
| Setup per part | 2h |
| Number of parts (blades) | 4 |
| Deposit efficiency | 0.9 |
| Powder gas ratio | 0.05 |
| Ambient temperature | 20 °C |
| Heated temperature | 500 °C |
| Coating thickness | 0.3 mm |
| overspray ratio | 0.05 |

The total cost and the cost components were calculated for all propeller sizes using MATLAB script. The plot created by the script allows the cost structure and sensitivity of the costs to propeller size to be analysed. This plot can is presented in Figure 38.

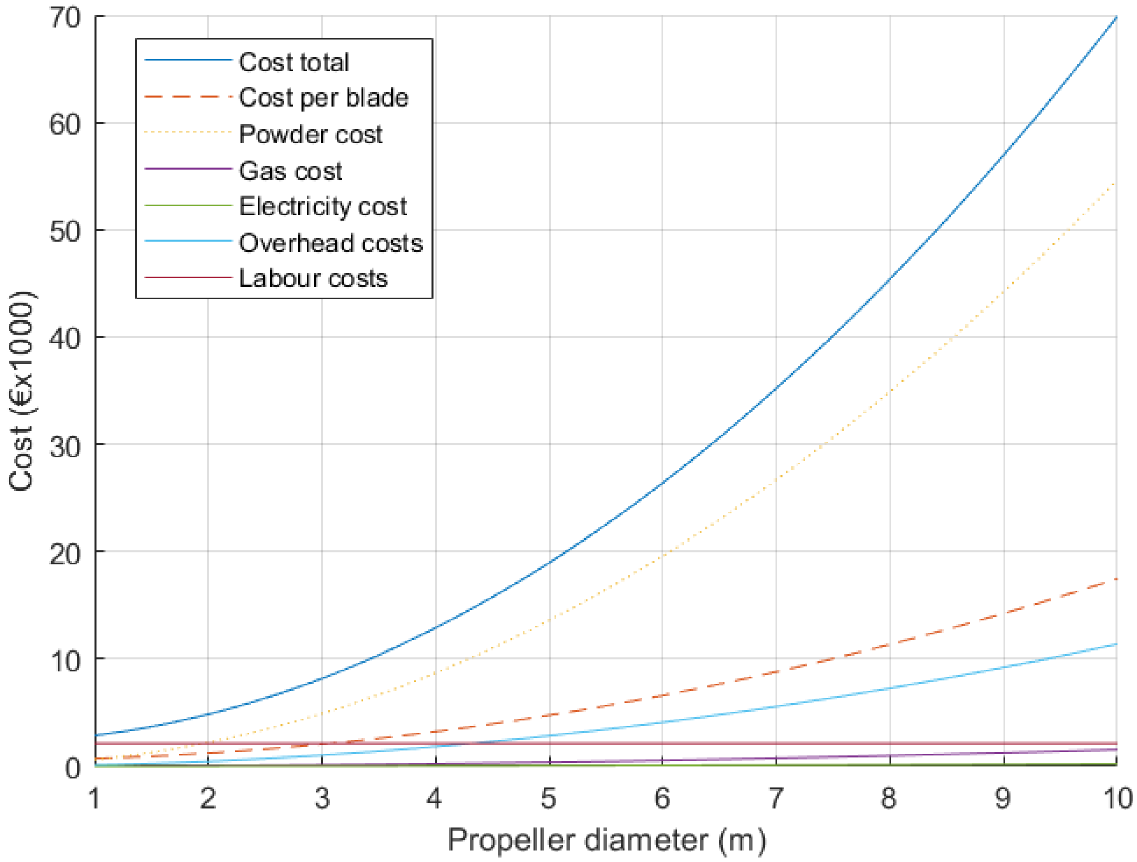


***Figure 38. Cost structure and the sensitivity to propeller size.***

The calculation of the results show that the labour costs are the most significant costs for small propeller sizes. For larger propellers, the material costs and more importantly powder cost becomes the most significant cost. The values used for the analysis are estimations, which can differ from real world values. For more accurate analysis, it would be important to discuss the project with individual suppliers to gain understanding of the true resource costs, especially for the most important cost factors such as powder and overhead costs. Other important factor is the used coating thickness, which directly affects the required coating material volume. It must be noted that the analysis does not include the possible logistic costs, profit margins and other costs associated with coating the propeller in practice. The logistics costs can be significant for large propellers, even to such extent that for very large propellers it may be better to transport the propeller spraying equipment to the shipyard to spray the propeller instead of transporting the propeller. The complete MATLAB script used for the cost analysis can be found in appendix B.

# 6. CASE STUDY

This chapter discusses in depth the financial feasibility and qualitative properties of the propeller coatings and repairs conducted using cold spray.

## 6.1 Coated Propeller

The aim with coated propellers is to gain benefit both by lowering the manufacturing costs of the propeller and by increasing hydrodynamic efficiency of the propeller. In this chapter the costs of coating a propeller are compared to the cost reduction and efficiency benefits.

### 6.1.1 Savings from increased efficiency

Estimating the overall performance of propeller is a complex problem that is well beyond the scope of this study. For this reason, the financial potential of the coating is approached with an assumption that the coating can improve the efficiency of the propeller. In practice this may be archived by fabricating the propeller from stronger base material, reducing fouling by applying anti fouling coating or by improving efficiency by reducing cavitation by using cavitation resistant coating. With this assumption made, the financial potential of the coating can be calculated and compared to the costs and risks, before committing on conducting a study on stronger propellers.

To efficiently analyse this problem, a MATLAB script was constructed to estimate engine power of a vessel as a function of propellers size. This function was used to estimate the yearly fuel consumption for a vessel with given propeller size. The yearly fuel consumption was compared to selected increases in efficiency to analyse the net present value of assumed efficiency gains.

Formula for connecting main engine power and propeller diameter is given in Equation 1, where $n_M$ is propeller rotations per minute (r/min), $D_{prop}$ is propeller diameter in meters, $P_M$ is main engine power (kW) and $C$ is a constant which reflects average values for ships with certain type of FP propeller. (MAN Diesel & Turbo , 2012)

$$n_M = C * \sqrt[3]{\frac{P_M}{(D_{prop})^5}} \quad (1)$$

For deriving power requirement as a function of propeller size, the propeller rotations per minute is replaced with constant propeller blade tip speed $v_{tip}$ as seen in Equation 2.

This is done to change the propeller rotations per minute which is a variable changing based on the propeller size to tip speed, which is a design value that can be constant regardless of propeller size.

$$n_M = \frac{60 * v_{tip}}{D_{prop} * \pi} \quad (2)$$

$$\frac{60 * v_{tip}}{D_{prop} * \pi} = C * \sqrt[3]{\frac{P_M}{(D_{prop})^5}} \quad (3)$$

Required main engine power for given propeller diameter and tip speed can be calculated using equation 4.

$$P_M = \frac{D_{prop}^2 * 60^3 * v_{tip}^3}{C^3 * \pi^3} \quad (4)$$

Fuel consumption of the vessel can be estimated from the main engines brake specific fuel consumption (BSFC), yearly engine running hours and from the operating profile or the average running power of the vessel. The brake specific fuel consumption is of course a variable depending on the engine loading and rotational speed, so an average value for the selected operation profile must be selected. BSFC value of 0.182 kg/kWh was selected based on available consumption data on marine engines. Ships with conventional shaft line are designed so that the peak efficiency of the propulsive system is at the most used operating point. For vessels operating in non-ice conditions this design point is often 85 % of the maximum engine power, so a 15 % sea margin is left for rough seas and other adverse conditions. (MAN Diesel & Turbo , 2012) As a ship spends some time manoeuvring, the average load was assumed to be 80%. Due to maintenance and port stays the ship is assumed to sail around 260 days a year, which translates to 6240 h of main engine usage per year. To translate the fuel consumption to financial cost an average fuel price must be assumed for the analysed price period. Fuel prices are very volatile by nature so estimating the future prices is difficult. For this analysis fuel prices are 300 $/mton for high sulphur oil fuel (HSOF) and 550 $/mton for very low sulphur oil fuel (VLSOF) were selected. The calculated main engine power and yearly fuel costs based on the selected assumptions is presented in Figure 39.

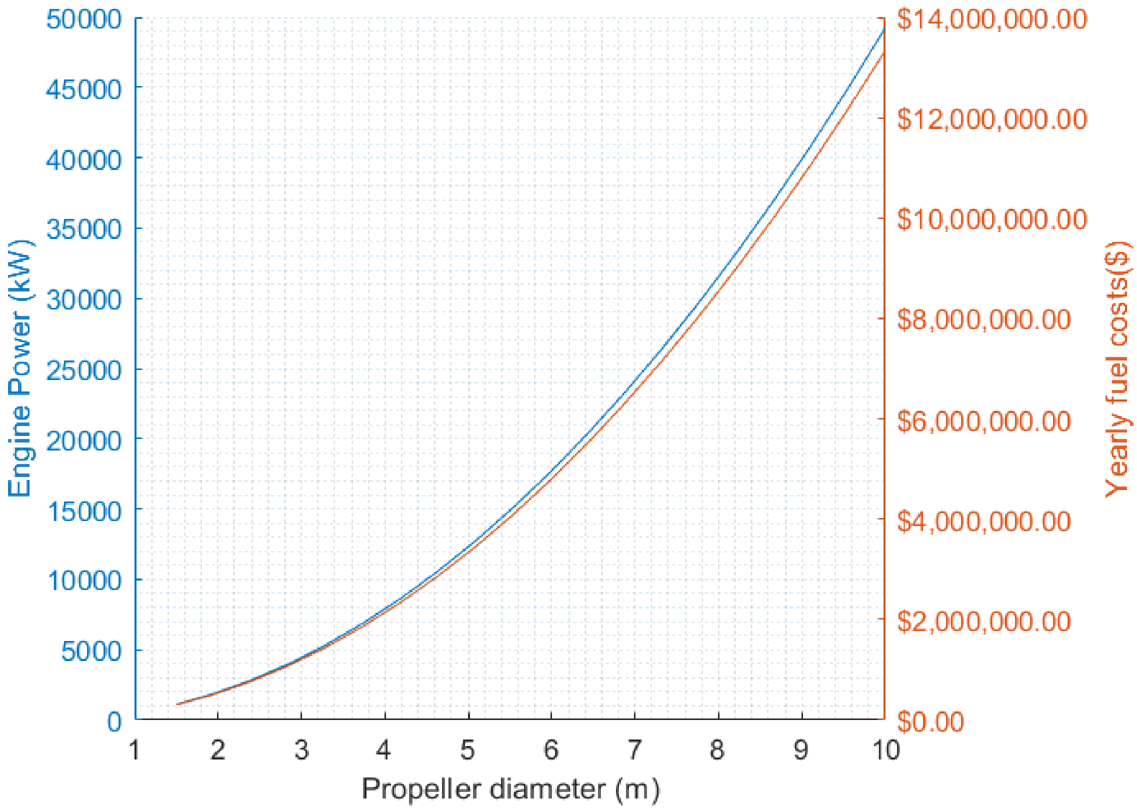


***Figure 39. Main engine power and yearly fuel costs as a function of propeller size.***

Based on the calculated fuel consumption and assumed 1% reduction in fuel consumption of the vessel a net present value can be calculate for the efficiency improvement. Figure 40 presents the net present value of 1 % efficiency improvement for multiple propeller sizes as a function of the propellers operating life, when a 10 % discount interest rate is used.

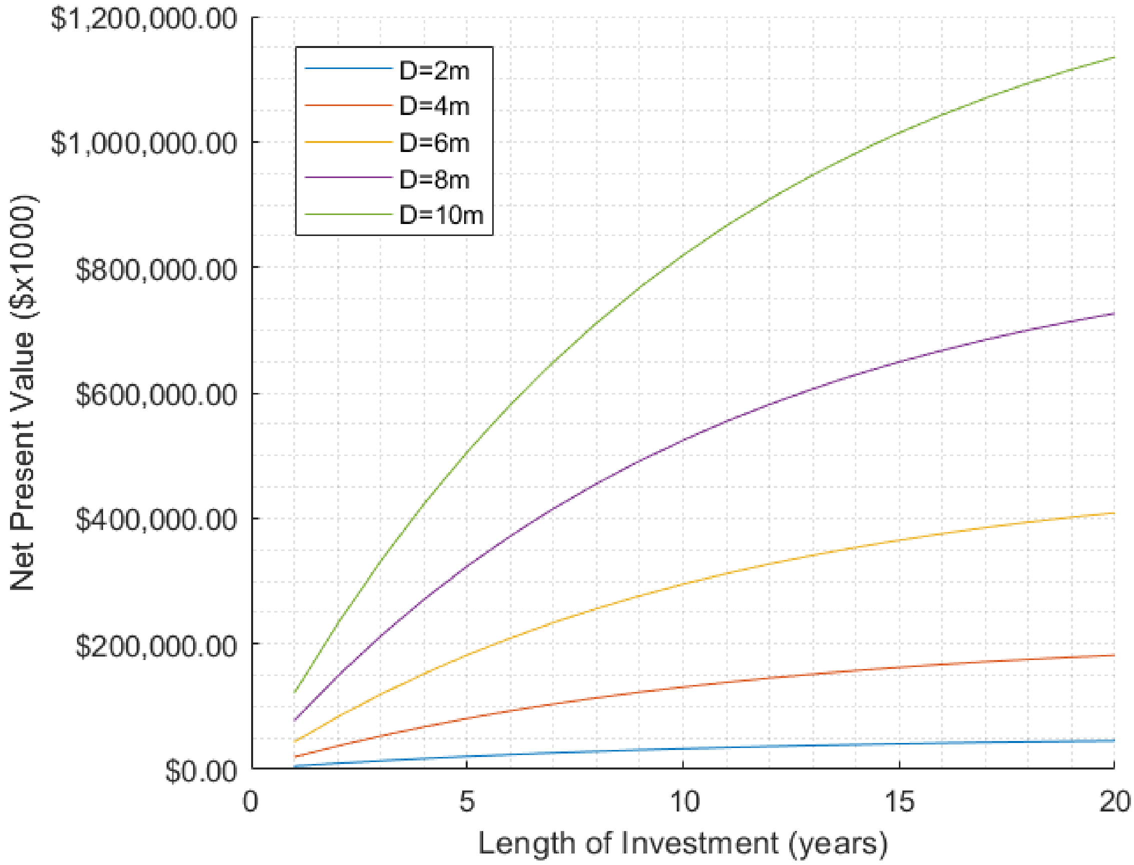


***Figure 40. Net present value of 1% efficiency improvement for multiple propeller sizes.***

If the propeller's operating life and so the length of investment is assumed to be 20 years, a single net present value can be calculated for any propeller size. The net present value of the 1% efficiency improvement over 20-year length of investment and propeller coating costs as a function of propeller size are presented in Figure 41.

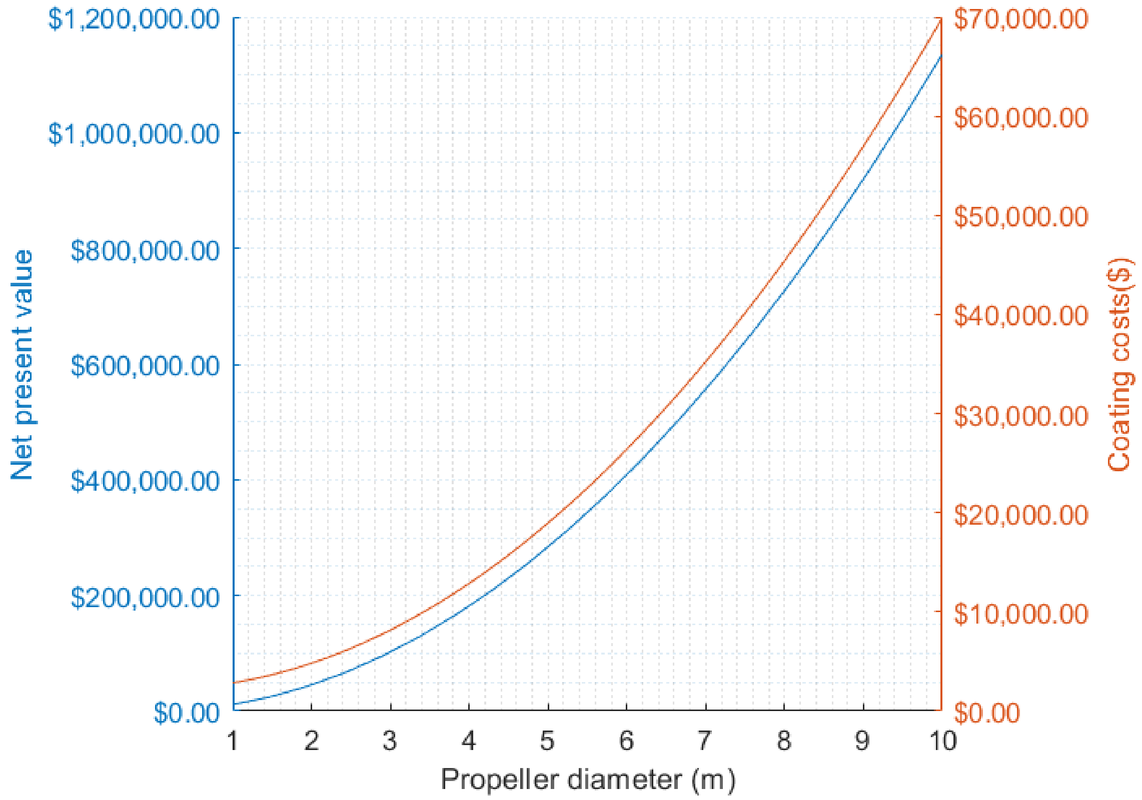


***Figure 41. Net present value of 1% efficiency gain compared to estimated coating costs.***

As can be seen, the net present value of the 1% savings greatly exceed the coating costs, even if the costs are assumed to double from profit margins and logistical costs. Still it is worth noting that the net present value is small compared to the total fuel costs during the 20-year period. The developed fuel cost estimation model is based on the assumed operating profile, engine power and gained efficiency. The described approach can be used to estimate the scale of the possible financial savings. More accurate values based on simulations and numbers of the individual use case should be used to determine the real-world saving potential for given vessel.

### 6.1.2 Savings potential from propeller material

Total costs caused by the material selection are not restricted to the cost of the bulk material. In propeller fabrication the material selection affects the cast ability, required melting temperature and therefore energy consumption, machining costs etc.

When comparing the most commonly used propeller materials, austenitic stainless steel propeller costs around twice as much as nickel aluminium bronze propeller of the equal size and shape, while martensitic propellers are reported to be by a factor more expensive than comparable austenitic stainless steel propellers. The cost effectiveness of the bronze materials is likely due to the easier cast ability of the material, lower energy consumption and lesser equipment needs, and due to the fact that bronze propeller fabrication is more common, so the competition in the field is stricter. With this being said, coated low-alloy steel propeller more likely has cost advantage against stainless steel than bronze propellers, as material cost of unalloyed and alloyed steels are significantly less than that of stainless steels (Masi, et al., 2019).

Also judging by its overall properties coated propeller is more likely competitive against stainless steel propeller as such propellers are more often used in ice-applications where the propellers are conservatively shaped due to extra ice loads. In these cases, extra strength of the propeller material can convert to more optimized propeller shape and thus better hydrodynamic efficiency. Additionally, as stainless-steel material does not possess any anti fouling properties, the long-term efficiency of the propeller is not compromised by coating material selection, when compared to bronze propeller.

### 6.1.3 Conclusion: coated propeller

Judging by the preliminary cost estimation, the coating of the propeller can be financially viable if the coating can provide efficiency gains through some means and if the coating can technically work in the intended application. The coated propeller can most likely bring benefits when compared to stainless steel propellers, as then largest cost saving can be made in material price, efficiency can most likely be improved, while no anti fouling properties are removed by the material selection.

Literature review of the coating materials suggests that from protection and sprayability standpoint the best compromise is to use nickel based alloy for the coating, as nickel has good corrosion and cavitation resistance while being able to be sprayed to form dense barrier coatings. Coating with anti-fouling paint system can be beneficial, as it improves the long-term efficiency of the propeller by reducing fouling while protecting the propeller from erosion and mishandling.

Practical test should be conducted to determine the true world performance of the corrosion protection coating. Additionally, the cold spray method should be compared to other coating and cladding methods such as laser metal deposition and weld cladding. Also, other thermal spray methods such as electric arc spraying or HVAF could be of evaluated.

Design studies should be done based on the assumed propeller material and coating properties to determine if performance gains and cost savings can be found for selected applications.

Due to the nature of the thin coating, the coated propeller is prone to erosion and damage from both marine environment and maintenance activities such as propeller polishing. Additionally, defects in the coating can compromise the protection and integrity of the coating. For these reasons it may be beneficial to further seal and protect the coating using an additional polymer coating. In addition to the increased protection, the suitable polymer coating can have anti-fouling properties which can improve the long-term efficiency of the propeller. It is also advisable to protect the propeller by cathodic protection to prevent corrosion in case of defects at the coating.

Efficient coating of large propellers requires special coating system to be build and the process optimized for reliable results. To archive this, it is important to discuss the project with cold spray equipment manufacturers and powder suppliers to find the appropriate equipment, process parameters and materials.

## 6.2 Propeller repair and cavitation protection

This chapter discusses the uses of cold spray for repairs in marine thrusters. When considering repairing a component, the repair must provide some benefit such as reduced cost or reduced lead time when compared to using a new replacement part. Then again when comparing repair methods, it is important to consider which repair method can archive the wanted performance in the most cost-effective manner.

Cold spray has been used to repair corrosion and erosion damage on aerospace applications. The documented repair applications include corrosion, erosion, fretting damage repair and restoration of bearing bores on aluminium and magnesium components such as gearbox casings. In these applications the cost of replacing the part is very high, the repair is difficult to do using competing methods and a lead time for new part is long. (Moog Aircraft Group, 2018; Honeywell, 2017; Champagne, 2008) In these applications the most prominent benefit of cold spray is the low heat input to the part when compared to the traditional welded repair. High heat input from welding alters the heat treatment of the welded area and induces residual to the part. These stresses often warp the part while also causing reduction in the fatigue life of the part. Due to the distortion areas with accurate fits and tolerances would need to be machined again, which is often impossible without filling the originally machined features. (Honeywell, 2017)

### 6.2.1 Alternate methods

In order to find applications where the cold spray would be effective over conventional repair methods, the strengths and weaknesses of the methods need to be assessed. Cold spray is a material adding method, so it is natural to compare it to alternative material fill methods, which are welding, polymer fillers and other thermal spray methods.

Welding repair consists of removing material affected by cavitation and corrosion, filling the repair area with filler material, and then grinding the area back to its original from. Welding is currently most commonly used and the most successful method of repairing cavitation damage as it essentially replaces the material loss with new material which has similar properties to the original. Main drawbacks of welding are related to its high heat input. Post welding heat treatment of the heat affected zone is often needed even for non-structural spot repairs to restore the original mechanical properties and corrosion resistance of the material. For these reasons welding repair can be time consuming even if the actual material loss is small, as the area affected by the cavitation can be large. (Germanischer Lloyd Aktiengesellschaft, 2019; Duncan, 2000; Ruzga, et al., 1993)

Non-fused materials such as epoxy putties have been used to fill cavitation and erosion damage. According to Duncan a major difficulty with non-fused materials has been poor adhesion to the substrate material, which leads to rapid deterioration of the repair. Such repairs are often considered temporary, so a follow up repair using welding is often done later. In this case the repair material needs to be removed before the long-term repair can be performed. (Duncan, 2000) Epoxy filler materials are cheap to acquire, and they can be applied quickly. For this reason, they can be an effective solution as onsite temporary repair when a long-term repair can be performed in a near future. (Ruzga, et al., 1993). According to Ruzga et al. the service life of epoxy coatings in hydroelectric turbines has been short, ranging from 6 months to one year. Repair using epoxy fillers consists of preparation where the surface is cleaned and roughened, application of the filler, and shaping of the filler after it has dried. (Duncan, 2000; Ruzga, et al., 1993)

### 6.2.2 Cold spray repair

Judging by the advantages and limitations of the cold spray process, repair of cavitation damage with no structural requirements is a clear application for the process. Cold spray can be used to deposit material similar to the original propeller material to a large area quickly without inputting heat to the component. The use of different thermal spray methods for providing cavitation protection for marine applications have been studied. Krebs studied the use of various thermal spay processes to deposit nickel aluminium bronze and other bronze alloys to repair cavitation damage on ships rudders. The study concluded that that HVOF, cold spray, warm spray process could produce deposits with satisfactory properties, with the cavitation resistance of cold and warm sprayed deposits being close to that of bulk material. (Krebs, 2016) Figure 42 presents the cavitation rate comparison between the different spray processes. Other properties of cold sprayed bronze are discussed in chapter 4.3.4

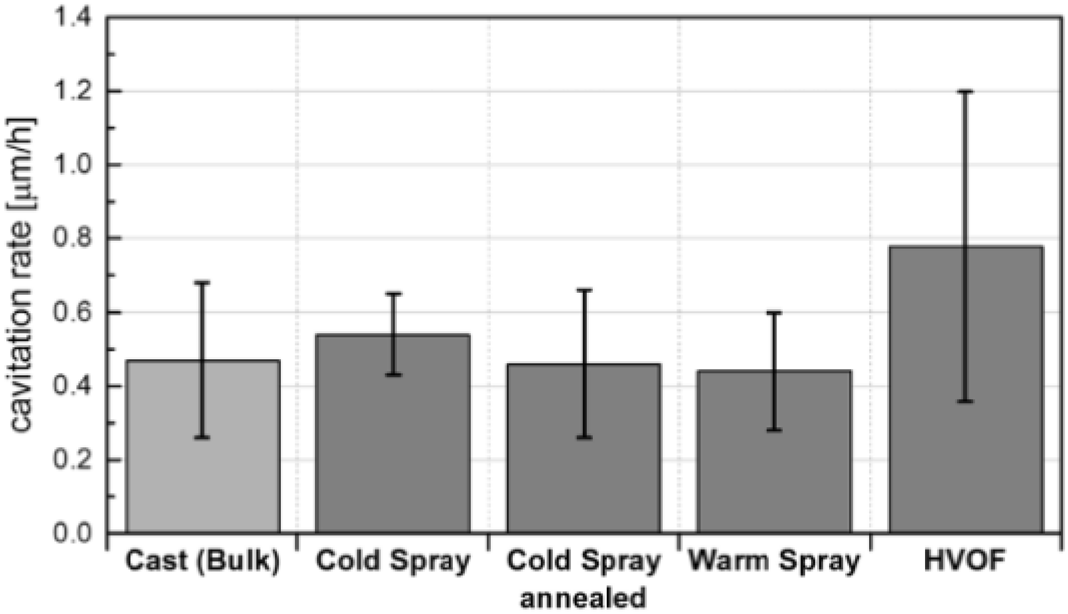


***Figure 42. Best cavitation rates attained from NAB samples deposited by different spray processes. (Krebs, 2016)***

The use of HVOF and cold spray process has been evaluated for repair of stainless-steel components used in hydropower applications. Jiang et al. studied the use of cold spray to repair cavitation damage on hydropower applications. The study found that cold sprayed AISI 316 stainless steel exhibited better cavitation erosion resistance than bulk material. The cavitation resistance of sprayed Inconel 625 was by a magnitude better than that of other tested materials. Galvanic potential of Inconel 625 is quite similar to that of stainless steels, so it may also be a usable material for repair of stainless-steel propellers. (Jiang, et al., 2020) Figure 43 presents the relative cavitation resistance of materials tested by Jiang et al.

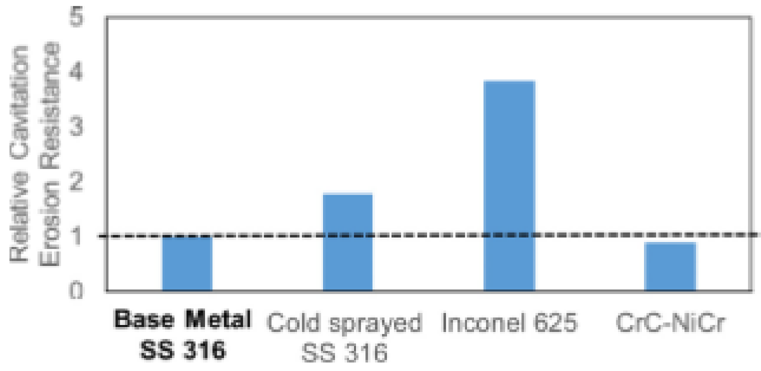


***Figure 43. Relative cavitation erosion resistance of tested materials. (Jiang, et al., 2020)***

Jiang et al. mentions that US Army Research Lab, VRC metal systems and Moog who are developing together with Pacific Northwest National Laboratory an onsite cold spray system for hydropower components. (Jiang, et al., 2020)

### 6.2.3 Conclusion: propeller repair

Main benefits of using cold spray over welding is its ability to deposit materials without inputting heat to the substrate. Cold spray can be used to fill large surface area of cavitation damage in shorter time when compared to welding method, without the need of pre or post heating the component when high structural properties are not required from the material. The bonding strength and cavitation resistance of the cold sprayed material is most likely better than that of polymer fillers.

Surface preparation need can be less than that of welding or polymer coating as cold spray equipment can be used to blast the substrate before spraying. Cold spray process is by nature largely self-cleaning, as non-adhering particles effectively blast the substrate surface. It is also probable that cold spray repair can be conducted by less experienced worker when compared to welding. Additional study should be conducted on which thermal spray method is the most practical for onsite repair for propeller of given material, given the limitations of portable thermal spray equipment.

# 7. CONCLUSION

The financial feasibility of the coated propeller was analysed using the MATLAB script. The net present value of the assumed efficiency gains compared to the estimated coating costs indicate that the coating of the propeller can be financially viable if the coated propeller can provide long term efficiency gains through improved propeller design, reduced surface erosion or reduced fouling. The coated propeller can most likely bring benefits when a stainless steel propeller is replaced by a coated propeller, as then the largest cost saving can be made in material price, most efficiency improvements can be made, while no anti fouling properties are removed by the material selection. Literature review of the coating materials suggests that from protection and sprayability standpoint the best compromise is to use nickel-based alloy for the coating, as nickel has good corrosion and cavitation resistance while being able to be sprayed to form dense barrier coatings. The thin coating is more prone to erosion and damage from both marine and maintenance activities such as propeller polishing, so the use additional anti-fouling coating system could be advisable, to further protect the coating and to improve the long term efficiency of the propeller.

Literature review of the coating materials, their properties and parameters used for their spraying suggest that cold spray can be a good alternative to be evaluated for repair of non-structural spot damage and for repair of low-level cavitation damage spread over large area. In these cases, cold spray can likely reduce cost of the repair by reducing the repair time when compared to welding repair. While cold spray might be usable for structural repairs when a heat treatment is employed, the benefits over traditional repair methods are lost.

# 8. FUTURE RESEARCH

Design studies should be done based on the assumed propeller material and coating properties to determine if performance gains and cost savings can be found for selected applications. Given the results of such studies, practical test should be conducted to determine the true world performance of the corrosion protection coating. Additionally, the cold spray method should be compared to other coating and cladding methods such as other thermal spray, laser metal deposition and cladding by WAAM/CMT methods.

Coated propellers are not yet recognized by classification societies, which currently prevents them from being used in practice. To receive the recognition of classification societies, practical tests must be conducted.

Coating thickness requirement and the overall performance could be estimated by coating areas of normal propellers of various vessels operating in different conditions. This would provide valuable information about the performance of different coatings in true operating conditions in cost effective manner.

Propeller repair using cold spray can be evaluated in practice by conducting test repairs on selected propellers, with different levels and types of cavitation damage. The repair procedure can be documented so the experience and information can be used to compare the method to currently used welding repairs.

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# APPENDIX A – NET PRESENT VALUE SCRIPT

```
% Net present value of coated propeller

fuelPrice = 300 % 300 $/mton for HSFO, 550 $/mton for HSFO
saving = 12 % mton/year, Fuel savings per voyage.
tripCount = 10 % Yearly voyages
yearlySaving = (fuelPrice*saving*tripCount)/1000 % Convert to x1000$

%% Present value of single data point

cf = yearlySaving
t = 15
r = 0.1
npv = 0
for l=1:t
    npv = npv + cf/((1+r)^t)
end
npv = npv % Net presen value 1000 €

%% Plotting loop

% Initial data
cf = yearlySaving
R = [0.15,0.10,0.08,0.06,0.04,0.02] % Studied interest rates
T = [1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20]

% Initialize
resultM = zeros(length(R),length(T))
x = linspace(1,length(T),length(T))


for n=1:length(R) % For all interest rates r
    r = R(n) % Get current interest rate
    for m=1:length(T) % For all investment period lenghts t
        t = T(m)
        npv = 0; % Zero npv for calculation
        for i=1:t
            npv = npv + cf/((1+r)^i); % Calculate npv for current parameters.
        end
        resultM(n,m) = npv; % Save results.
    end
end

% Create figure
FigH = figure
hold on
set(FigH,'Name', 'This is the figure title')
set(FigH,'Color','white')

% Plot results
for i=1:size(resultM,1)
plot(x,resultM,'DisplayName','r='+string(R(i)))
end

% Figure visuals
% title('Net Present Value for different interest rates and investment periods')
xlabel('Length of Investment (years)')
ylabel('Net Present Value ($x1000)')
grid on
hold off
```

# APPENDIX B – COST ANALYSIS SCRIPT

```
%% Spray cost estimator
% MATERIAL PROPERTIES
coating_density = 8800 % kg/m^3. 8800 for Monel 400
material_price = 100 % kg/m^3. 100 for Monel 400
carrier_gas_price = 0.14 % €/kg 0.14 for nitrogen, 30 for helium
electricity_price = 0.15 % €/kWh
cp_nitrogen = 1.05 % kJ/(kg*K)
labour_price = 75 % €/h
% SYSTEM PROPERTIES
deposit_rate = 0.4 % kg/min. 0.4 for Monel 400
deposit_efficiency = 0.9 %
powder_gas_ratio = 0.05 % percentage of powder mass per unit of gas
ambient_temperature = 20 % room temperature
heated_temperature = 500 % gas temperature
hourly_rate = 500 % Price per machine hour
% JOB PROPERTIES
pre_spray_preparation = 20 % Total time of pre spray preparation. Program-
ming, tooling etc.
part_setup = 2 % Setup time per part
number_of_parts = 4 % Number of individual parts / blades
coating_thickness_mm = 0.3 % Coating thickness in millimetres
overspray = 0.05 % Overspray coefficient = overspray percentage.
% CALC PROPERTIES
max_dia = 10 % meters, maximum propeller size for analysis
min_dia = 1 % metres, minimum propeller size for analysis
steps = 100 % Number of different sizes
% CALCULATION
syms d
% blade area equation in relation to diameter for ice propeller (SINGLE
BLADE).
% From fit from cad data
% Checked for accuracy.
egn = 0.47*d^2 - 0.054*d + 0.11 %
% Initialize matrices
m_dias = linspace(min_dia,max_dia,steps)
m_areas = zeros(1,steps)
calc_num = length(m_dias)
% Form propeller area matrix
for i=1:calc_num
    m_areas(i) = subs(egn,d,m_dias(i))
end
% Initialize matrices for data saving
m_time = zeros(1,calc_num)
m_cost_powder = zeros(1,calc_num)
m_cost_gas = zeros(1,calc_num)
m_cost_electricity = zeros(1,calc_num)
m_cost_equipment = zeros(1,calc_num)

m_cost_work = zeros(1,calc_num)
m_cost_per_part = zeros(1,calc_num)
m_cost_total = zeros(1,calc_num)
for i=1:calc_num % For all areas
    % Calculation
```

```
        coating_thickness = coating_thickness_mm / 1000 % used for calculations
        coating_volume = m_areas(i) * coating_thickness * number_of_parts % To-
tal volume of coating on part % Checked
        mass_of_powder  =  ((coating_volume  *  coating_density)/deposit_effi-
ciency) + overspray * coating_volume % Checked
        mass_of_gas = mass_of_powder / powder_gas_ratio
        Q_gas  =  mass_of_gas*cp_nitrogen*(heated_temperature-ambient_tempera-
ture) % Checked
        time_coating = mass_of_powder/(deposit_rate*60) % Time in hours.
        % Costs
        cost_powder = material_price * mass_of_powder
        cost_gas = carrier_gas_price * mass_of_gas
        cost_electricity = electricity_price * Q_gas/3600
        cost_equipment = 0 + (time_coating * hourly_rate)% Depreciation is not
yet accounted for.
        cost_work = (pre_spray_preparation + part_setup * number_of_parts ) *
labour_price % Total hours * labour rate
        cost_total = (cost_powder + cost_gas + cost_electricity + cost_equipment
+ cost_work)
        cost_per_part = cost_total / number_of_parts
        m_time(i) = time_coating
        m_cost_powder(i) = cost_powder
        m_cost_gas(i) = cost_gas
        m_cost_electricity(i) = cost_electricity
        m_cost_equipment(i) = cost_equipment
        m_cost_work(i) = cost_work
        m_cost_per_part(i) = cost_per_part
        m_cost_total(i) = cost_total
    end
    % PLOTTING
    f1 = figure
    set(f1,'Color','white')
    xlabel('Propeller diameter (m)')
    ylabel('Cost (€x1000)')
    hold on
    plot(m_dias,m_cost_total/1000,'DisplayName','Cost total')
    plot(m_dias,m_cost_per_part/1000,'--','DisplayName','Cost per blade')
    plot(m_dias,m_cost_powder/1000,':','DisplayName','Powder cost')
    plot(m_dias,m_cost_gas/1000,'DisplayName','Gas cost')
    % plot(m_dias,m_cost_electricity/1000,'DisplayName','Electricity cost')
    plot(m_dias,m_cost_equipment/1000,'DisplayName','Overhead costs')
    plot(m_dias,m_cost_work/1000,'DisplayName','Labour costs')
    grid on
    hold off

    % PLOTTING
    f2 = figure
    set(f1,'Color','white')
    xlabel('Propeller diameter (m)')
    ylabel('Time (h)')
    hold on
    plot(m_dias,m_time,'DisplayName','Machine time')
    hold off
```