Corrosion Analysis of Autonomous Underwater Projectiles Launched from a Host Vehicle

A Naval Undersea Warfare Center Research Initiative

CHE 534: Corrosion and Corrosion Control
Final Term Paper
Corey Murphy
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Summary Conclusions

- Improving corrosion resistance of autonomous underwater projectiles will increase Navy intelligence
    - Beneficial for the safety and security of the United States of America
- Stainless steel ideal choice of metal for construction of projectiles
    - Better corrosion resistant characteristics and less expensive than aluminum
    - Alloy 2507 duplex stainless steel optimal grade
        - Excellent for protecting against corrosion in harsh seawater environment
- Cathodic protection will provide additional corrosion resistance to projectiles
    - Sacrificial anode coating/plating is relatively inexpensive for the additional gain in corrosion resistance
        - Galvalum I is the preferred material for sacrificial anode due to effectiveness in submerged seawater conditions

Introduction

The *Methodology for Underwater Deployment from a Host Vehicle* project is a research initiative sponsored by the Naval Undersea Warfare Center (NUWC) with the overarching goal of increasing the range of the Navy's undersea weapons and/or range of research craft. The focus of the project entails developing a system that would allow for multiple autonomous underwater projectiles to be launched from a host vessel. Currently, underwater launching primarily consists of one device utilized one time from a submarine or other large ship. NUWC has continued to work on expanding these capabilities with research initiatives such as this one in collaboration with the University of Rhode Island and other universities across the country.

The host vessel itself will be designed as a modified torpedo that has the capacity to transport multiple smaller payloads. In this case, the smaller payloads will be autonomous underwater projectiles. The host vessel will be deployed from a larger Navy vessel (submarine or ship) and will transport the smaller projectiles to underwater regions where they can be launched and travel autonomously short distances to locations that larger vessels could not logistically reach. In military applications, these projectiles have the potential to more covertly deploy weapons, drones, or other equipment in areas where a full-sized submarine/ship either would not be able to physically reach or be able to reach undetected. In research applications, the host could be used to reach areas inaccessible to any manned vehicle and deploy probes, tags, or any other data collection technology.

Due to the level of secrecy required around NUWC research initiatives and the recency of the project launch, dimensional specifics of the projectiles have not yet been provided. For the purpose of this research paper, the geometry of the projectile is assumed to be a small cylindrical pressure vessel that would fit compactly within a torpedo shaped host vessel.

The following research paper is a complete corrosion analysis of the small autonomous underwater projectiles that specifically would be utilized for Navy research and surveillance purposes. The goal of this paper is to identify and understand the best methods of improving the corrosion resistance of the projectiles based on the harsh seawater environments they will be subject to. The material selection for the design of the outer surface of the projectiles will be considered as will other processes of corrosion protection that could be implemented. Lecture notes from Dr. Richard Brown's Corrosion and Corrosion Control course serve as the main knowledge basis for this paper. Several supplemental references (listed at the end of this paper) were also utilized to aid in the research for this project and will be introduced throughout the paper.

Material Selection

One of the key contributors to determining the projectile's corrosion resistance is the material selected for the outer surface of the design. In order to determine the correct material for the specific application, it is crucial to consider the environment in which the projectile will be subject to as well as the length of time the projectile will be required to operate within this environment. Two types of metals will be compared and analyzed in this section for the given application. The first is aluminum and the second is stainless steel. Once one of these metals is selected, the specific grade of metal can then be determined.

Environmental Factors

These projectiles will need to be capable of operating in harsh seawater environments at varying depths below sea level for extended periods of time. Seawater is considered a particularly corrosive environment, especially on metals, due to a few main influencing factors. The first is the high salt content of seawater when compared with fresh water[6]. The salt content in water directly affects the conductivity and oxygen content of water. With an increase of salt content in water, the electrical conductivity of water increases while the oxygen content decreases. For some metals, water with lower levels of salinity can be beneficial due to the calcium and magnesium ions contained in the metal surface precipitation of calcium carbonate and magnesium hydroxide, forming a protective coating over the metal. Unfortunately, the chloride in seawater can destroy this oxide surface film by producing hydrogen ions during hydrolysis, increasing the acidity of the seawater, and therefore increasing the possibility of localized corrosion.

Another corrosion influencing factor of seawater on metals is its conductivity[6]. Most of the salt content in seawater is in the ionization state, making the seawater a good conductor of the electrolyte. This will only serve to accelerate any type of corrosion that is occurring on the metal. Similarly, the more dissolved oxygen present in the seawater, the higher the electrode potential of the metal as dissolved oxygen will diffuse faster toward the cathode, increasing the corrosion rate of the metal. For certain grades of aluminum and stainless steel, a thin protective layer of oxide film will form when the metal is oxidized, increasing corrosion resistance by maintaining a passive state. This is an important characteristic of these metals and it is crucial to consider for corrosion prevention.

Length of Missions

For research applications, the underwater projectiles must be capable of not only reaching their required destination, but also remaining operational in that location for an extended period of time. Once the projectiles are deployed from the host vessel, they will travel a short distance autonomously to the previously unreachable destination. The projectile containing various sensors/data acquisition technology will then remain at the sea floor motionless for months, possibly years, to carry out research duties. This means that the projectiles must be durable and be capable of resisting detrimental corrosion for the length of the study.

The projectiles must also be versatile regarding the depths below seawater that they can withstand. Missions that require the projectiles to be stationed at large depths below sea level will require a metal that can withstand the elevated levels of pressure for long periods of time.

Aluminum

One of the great benefits of aluminum is that it is relatively lightweight when compared with many stainless steel alternatives. The projectiles will be tasked with traveling a short distance after being deployed from the host vessel, so a lightweight design would lower the amount of propulsion required for service. Aluminum also does not rust unlike irons and steels.

Although aluminum does exhibit some acceptable corrosion resistant properties, seawater may prove to be too harsh on the metal. In water with smaller levels of salt content, the thin coating of aluminum oxide that forms a shield on the metal's surface would be sufficient for protecting against corrosion. Seawater however contains elevated levels of salinity that would create a chalky coating of aluminum oxide along the surface, opening the opportunity for unpleasant pitting corrosion to take place. In order for aluminum to be safely used in marine applications, additional corrosion protective processes such as a coating or sacrificial anode must be employed[5]. These processes would require maintenance overtime which logistically would not be feasible due to the unreachable regions the projectiles would be stationed. Aluminum also tends to be more expensive than many stainless steel options.

Despite the clear benefit of weight saving that aluminum presents, the metal presents too many other obstacles to consider it a viable option for this application. The projectiles will not have to travel far once deployed as the host vessel will be the primary method of transportation. This stage of autonomous travel only represents a very small portion of the projectile's overall life cycle. The corrosion resistance characteristics of aluminum are not suited for an extended life in a harsh seawater environment. The benefits gained from decreasing the weight of the projectile do not justify the steeper price nor the lack of corrosion resistant characteristics of aluminum. Stainless steel alternatives should instead be considered.

Stainless Steel

Stainless steel is an alloy that contains a high content of chromium. The benefit of this elevated chromium content in regards to marine applications is the passive chromium oxide film that forms to prevent surface corrosion by blocking the diffusion of oxygen into the steel. This property greatly enhances the corrosion resistance of the alloy, making stainless steel an ideal choice for use in seawater. When compared with aluminum, stainless steel also tends to be less expensive. Stainless steel can be susceptible to small amounts of pitting and crevice corrosion due to the breakdown of the passive oxide film on the alloys surface when subject to chloride-rich environments. Despite this, the level of corrosion that stainless steel would endure due to extended exposure in seawater would not be as detrimental as the corrosion that would occur to aluminum. Due to the significantly improved corrosion resistance in seawater and lower price when compared with aluminum, stainless steel is the best choice of metal for the design of these underwater projectiles.

As stated above, the chromium content of stainless steel is the main factor that influences the alloy's corrosion resistance to seawater. Stainless steels with higher contents of chromium prove to be more resistant to localized pitting corrosion. For this application, it is important to select a stainless steel with a high chromium content. To determine the alloy's resistance to pitting corrosion, the Pitting Resistance Equivalent Number (PREN) should be calculated. This number depends on the alloy's chromium, molybdenum and nickel content. The equation below is used to calculate the PREN of a stainless steel:

$$PREN = \%Cr + 3.3(\%Mo) + 16(\%N)$$

The larger the PREN, the greater the resistance to localized pitting corrosion. For marine applications, it is generally advised to select a stainless steel that has a PREN larger than 40 for optimal results.

Duplex stainless steels are a specific type of stainless steel that have a metallurgical structure consisting of two phases in roughly equal proportions: austenite (face-centered cubic lattice) and ferrite (body-centered cubic lattice)[2]. In contrast to single phase 300 grade austenitic stainless steels, duplex stainless steels are specifically designed to provide enhanced corrosion resistance characteristics. These characteristics include greater protection against chloride stress corrosion and pitting corrosion which many standard stainless steels can be susceptible to. Duplex stainless steels also tend to exhibit higher strength properties than 300 grade stainless steels. Higher strength may present a slight disadvantage as this will limit the alloy's formability/machinability. The projectiles will not require complex machining due to the simplistic cylindrical pressure vessel design, therefore this disadvantage is not a major issue. The additional corrosion resistance and higher strength will prove to be more advantageous for extending the life of the projectile at the sea floor.

Alloy 2507 is a duplex stainless steel that has many characteristics that would be beneficial for this specific marine application[1]. The table below displays the typical weight percentage values for alloy 2507.

Carbon	Chromium	Nickel	Molybdenum	Nitrogen	Others
0.020	25	7	4.0	0.27	S=0.001

Table 1: Alloy 2507 Weight % Values[1]

With contents that include 25% chromium, 4% molybdenum and 7% nickel, alloy 2507 has a PREN of 43. This is ideal as the PREN is greater than 40, ensuring excellent resistance to localized pitting corrosion. The high content of chromium and molybdenum also make the alloy extremely resistant to uniform corrosion from organic acids and inorganic acids containing high chloride levels. This is crucial as the alloy will be subject to high levels of chloride in the seawater environment. The figures below graphically display the isocorrosion curves (0.1 mm/year scale) of various metals versus alloy 2507 in two inorganic acids over an 80 C temperature range.

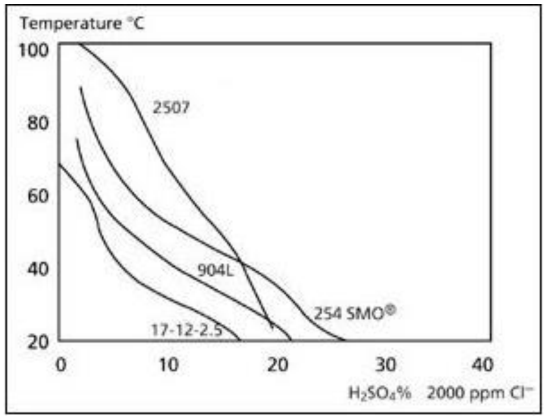

Figure 1: Isocorrosion Curves in Sulfuric Acid (Additional 2000 ppm Chlroide Ions)[1]

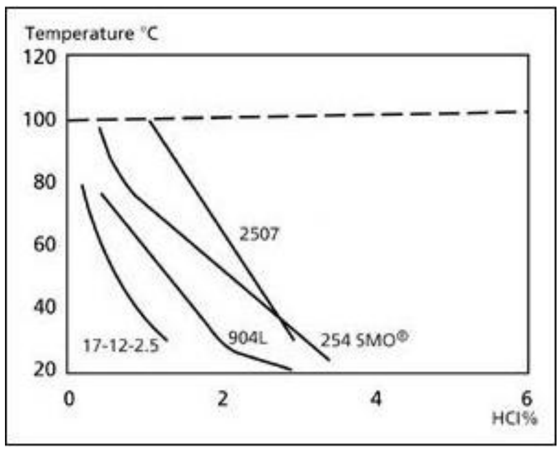

Figure 2: Isocorrosion Curves in Hydrochloric Acid (Broken Line = Boiling Point)[1]

The isocorrosion curve of alloy 2507 is above the curves of the compared metals, demonstrating the alloy's excellent corrosion resistance when subject to these two inorganic acids[1]. This performance should be maintained when alloy 2507 is submerged in seawater due to seawater's high chloride content.

Another great benefit of alloy 2507 is its low carbon content. This significantly lowers the risk of carbide precipitation forming at the grain boundaries during heat treatment, therefore making the alloy highly resistant to carbide-related intergranular corrosion. With heat treatment and welding being necessary manufacturing processes to obtain the correct geometry for the projectiles, this low carbon content is ideal. The duplex structure of alloy 2507 also provides excellent resistance to stress corrosion cracking (SCC).

In addition to the metal's excellent corrosion resistant characteristics, the metal also has high strength mechanical properties that would be capable of withstanding the pressure loads of the deep sea. These properties are most effective in environments with temperatures below 570 F which makes it a good choice for this application. The table below displays the mechanical properties of alloy 2507.

0.2% Offset Yield Strength, ksi	80 min.
Ultimate Tensile Strength, ksi	116 min.
1% Offset Yield Strength, ksi	91 min.
Elongation in 2 inches, %	15 min.
Hardness, Rockwell C	32 max
Impact Energy, ft-lbs	74 min.

Table 2: Mechanical Properties of Alloy 2507[1]

Due to the excellent corrosion resistant characteristics and high strength properties exhibited by this specific duplex stainless steel, alloy 2507 is the ideal choice of material for the construction of the underwater projectile's outer surface.

Corrosion Protection Processes

Alloy 2507 duplex stainless is excellent for preventing chloride stress corrosion and localized pitting corrosion due to its PREN of 43 and high chromium and molybdenum content. On its own, the alloy would perform admirably in a harsh seawater environment for long periods of exposure, meeting the design requirements. With that being said, there are also a few additional corrosion protection processes that should be considered to further improve the overall corrosion resistance of the underwater projectiles.

Weld Decay Protection

The projectiles will be cylindrical pressure vessels in design, mitigating the possibility of crevice corrosion occurring. In order to form the alloy 2507 into this desired geometry, heat treatment and welding will be required. Alloy 2507 is a high strength metal that will need to undergo some form of heat treatment to mold into a cylindrical shape. Luckily, the alloy does not lose much of its strength after undergoing heat treatment. Once this process in complete, the newly shaped alloy will need to be welded together to connect the cylinder. Additional welds will need to be completed to secure top and bottom caps to the cylinder, effectively closing off the enclosure. When introducing welds into the manufacturing process, the possibility of weld decay must be evaluated.

The main cause of weld decay comes from the stainless-steel being sensitized during the welding process, decreasing the corrosion resistance of the metal. When stainless-steel is sensitized, intergranular corrosion will occur locally to an area adjacent to the weld. This intergranular corrosion would create small leaks in the pressure vessel. The fully submerged projectiles will be carrying data acquisition technology, so any leaks in the vessel would result in catastrophic failure of the onboard electronics.

One of the major corrosion resistant characteristics of alloy 2507 is its high chromium content due to its ability to form a surface film of a rough, adherent, invisible, corrosion resisting chromium oxide film on the metal's surface. As stated in the previous section, another benefit of alloy 2507 is its relatively low carbon content. This is key for decreasing the potential of weld decay from occurring. Despite this, there is still a small chance for weld decay even with the small carbon content. The formation of chromium carbide occurs due to interstitial diffusion. The net effect of this diffusion is that the region adjacent to the grain boundaries becomes depleted in chromium by second phase formation, leaving a small region of non-stainless steel, thus reducing the stainless-steel's corrosion resistance. The second phase formation of chromium carbide is what leads to weld decay.

Thermal treatment is also necessary for the formation of chromium carbide. The carbide is stable between the temperature range of 950 F and 1450 F but requires time to grow due to the nucleation required for the second phase which grows on the grain boundaries. The fused region of the weld where the formation of liquid metal occurs is too hot and cools too rapidly for the stable chromium carbide region to form. Also, some areas that are farther away from the weld do not reach the required temperature range for the formation of stable chromium carbide. Only the areas away from the weld that do reach the required temperature range are able to form this stable chromium carbide, thus leading to weld decay. These are the areas where intergranular corrosion would most likely occur, creating small leaks on the projectiles.

To minimize the risk of weld decay, multiple techniques could be utilized. Typically, low power density welding techniques (torch welding) are more susceptible to causing weld decay. Using these techniques, heat is applied over a wide range which might allow for the formation of stable chromium carbide due to the required temperature range being reached. Certain forms of brazing should also be avoided. Higher power density welding techniques are preferred as the heat input is very concentrated, diminishing the possibility of the formation of the carbide. Alloy 2507 possesses good weldability and can be joined to itself by shielded metal arc welding, gas tungsten arc welding, plasma arc welding, flux cored wire welding or submerged arc welding[1]. Another preferred welding technique is utilizing low carbon welding rods. Although some of these improved welding techniques are more expensive than traditional lower power density welding, the risk of weld decay causing leaks that could damage internal electronics far outweighs the added cost. Quenching the alloy with air or water after welding and heat treatment also can prevent weld decay. It is recommended that alloy 2507 should be annealed at a minimum temperature of 1925 F directly following the quenching process[1]. These techniques should be used during the manufacturing process of the projectiles to minimize any remaining possibility of weld decay.

Cathodic Protection

Another corrosion protection process that is effective at preventing pitting corrosion (specifically in chloride rich environments such as seawater where the alloy would be surrounded by a conductive electrolyte) is cathodic protection[3]. Cathodic protection is a process that is popular in many marine applications such as the design of ship hulls due to the gain of additional corrosion resistance at a relatively low cost.

There are two different methods of cathodic protection that should be considered[3]. The first would be an impressed current cathodic protection system (ICCP). This system involves using an external DC current source and a variety of anode materials to supply the cathodic current. The benefits of using an ICCP include variable control of the current and potential as well as a long life cycle. The downsides however are the need for an external power source, the possibility of stray current corrosion and the complex installation and maintenance that must be completed on the system to achieve a long life cycle. The other cathodic protection option would be utilizing a sacrificial anode system. The benefits of this system are the low cost compared with an ICCP, the simple installation and the sacrificial anode requires no maintenance or supervision. The disadvantages of this system are the lack of variable control, the additional weight of the anode and the finite life of the anode. Although in theory an ICCP would seem to be the ideal choice due to a long life cycle, it would not be possible to perform any maintenance on the projectile once deployed and therefore an ICCP would also have a finite life cycle. Additionally, the complexity of adding an external power source to a projectile submerged in seawater poses too many risks of the system potentially failing. Therefore, a more simplistic approach of a sacrificial anode system would be the preferred choice for this application.

The basic concept of a sacrificial anode system involves attaching/applying a more anodic metal to the surface of the metal desired to be protected (alloy 2507). The more anodic metal surrounding the alloy 2507 (known as the sacrificial anode) would corrode first, therefore protecting the alloy 2507. In order to determine a suitable metal to act as the sacrificial anode, the electrochemical voltage of alloy 2507 relative to gold must be determined.

Anodic Index	Index (Volts)
Silver, solid or plated; monel metal. High nickel-copper alloys	0.15
Nickel, solid or plated, titanium an s alloys, Monel	0.30
Copper, solid or plated; low brasses or bronzes; silver solder; German silvery high copper-nickel alloys; nickel-chromium alloys	0.35
Brass and bronzes	0.40
High brasses and bronzes	0.45
18% chromium type corrosion-resistant steels	0.50
Chromium plated; tin plated; 12% chromium type corrosion-resistant steels	0.60
Tin-plate; tin-lead solder	0.65
Lead, solid or plated; high lead alloys	0.70
Aluminum, wrought alloys of the 2000 Series	0.75
Iron, wrought, gray or malleable, plain carbon and low alloy steels	0.85
Aluminum, wrought alloys other than 2000 Series aluminum, cast alloys of the silicon type	0.90
Aluminum, cast alloys other than silicon type, cadmium, plated and chromate	0.95
Hot-dip-zinc plate; galvanized steel	1.20
Zinc, wrought; zinc-base die-casting alloys; zinc plated	1.25
Magnesium & magnesium-base alloys, cast or wrought	1.75

Table 3: Anodic Index[7]

The table above is an anodic index table that lists the electrochemical voltage of various metals relative to gold. Gold is used as the reference metal due to its anodic index value of 0.0 V. This makes gold the most cathodic metal in the galvanic series. From the table, alloys from the 2000 series (which includes alloy 2507) have an anodic index value of -0.75 V. This would mean that the sacrificial anode selected for this application must have an anodic index less than -0.75 V. The larger the difference in electrochemical potential between the sacrificial anode and alloy 2507, the more protection the sacrificial anode will be capable of providing.

The three most widely used sacrificial anodes that are more electronegative than alloy 2507 are zinc, galvalum and magnesium. Each anode has their own unique preferred uses and set of properties which are displayed respectively in the tables below.

Anode	Preferred Use	Approx. Potential Volts ref. Ag/AgCl
Magnesium, High Potential	Soils with resistance > 2000 Ω-cm	-1.75
Magnesium, Standard	Soils with resistance < 2000 Ω-cm, and in aqueous environments with controllers if necessary	-1.50
Zinc, Hi-Amp	Seawater, brackish water, saline mud. Temps < 60°C	-1.05
Zinc, Hi-Purity	Underground, fresh water, and saline environments > 60°C	-1.05
Galvalum I	Submerged seawater, max. temp 25 °C	-1.05
Galvalum II	Saline mud	-1.04
Galvalum III	Seawater, brackish water, saline mud	-1.10

Table 4: Sacrificial Anode Types and Uses[4]

Property	Anode Material Type				
	Magnesium	Zinc	Galvalum 1	Galvalum II	Galvalum III
Density, kg/m^3	1940	7130	2700	2700	2700
Electrochem Equiv, g/coulomb	0.126E-3	0.339E-3	0.093E-3	0.093E-3	0.093E-3
Theoretical Ah/Kg	2,205	819	2,987	2,987	2,987
Current Efficiency %	0.55	0.95	0.95	0.57	0.85
Actual Ah/Kg	1,212	780	2,830	1,698	2,535
Actual Kg / Amp / Year	7.95	11.25	3.10	5.16	3.46
Potential V, ref. Ag/AgCl	-1.75	-1.05	-1.05	-1.04	-1.10

Table 5: Sacrificial Anode Properties[4]

From Table 4, Hi-Amp Zinc, Hi-Purity Zinc, Galvalum I and Galvalum III all can be used in seawater applications. Galvalum I's preferred use is on metals submerged in seawater which matches the required design specification for the underwater projectiles. Therefore, this specific sacrificial anode will be chosen for this application.

Maximizing the design life of the underwater projectiles is a crucial design specification to allow for extended Navy research studies. This means that the life cycle of the sacrificial anode should also be maximized to meet the desired specification. The life cycle of the sacrificial anode depends on multiple different variables. The equation below is useful for calculating the necessary amount (weight) of anode material required for the desired target design life[4]:

$$W = \frac{\left(8760\frac{h}{yr}\right)YC}{ZU}$$

Where *W* is the weight of anode material, *Y* is the target design life (years), *C* is the current demand (amps), *Z* is the anode capacity and *U* is the utilization factor. The utilization factor for Galvalum I is 0.9[4]. The current demand can be calculated using Ohm's law:

$$C = \frac{V}{R}$$

Where *V* is the reference driving potential and *R* is the anode resistance to ground. The driving potential is determined by anode type and can be found in Table 5. The anode resistance to ground can be calculated using the formulas in the table below.

Anode Type	Resistance Formula	
Long Slender stand-off L ≥ 4r	$R = \frac{\rho}{2\pi L}\left(\ln\left(\frac{4L}{r}\right) - 1\right)$	(Modified Dwight)
Long Slender stand-off L < 4r	$R = \frac{\rho}{2\pi L}\left[\ln\left\{\frac{2L}{r}\left(1+\sqrt{1+\left(\frac{r}{2L}\right)^2}\right)\right\} + \frac{r}{2L} - \sqrt{1+\left(\frac{r}{2L}\right)^2}\right]$	
Long flush mounted L ≥ 4 x width and thickness	$R = \frac{\rho}{2S}$	(Lloyds)
Short flush-mounted, bracelet and other flush mounted shapes	$R = \frac{0.315\rho}{\sqrt{A}}$	(McCoy)

Table 6: Anode Resistance to Ground Formulae[4]

Due to the cylindrical shape of the projectiles, the McCoy resistance formula for short flush-mounted, bracelet and other flush mounted shapes will be used. The sacrificial anode will essentially be a cylindrical exterior plate or coating that encapsulates the projectile so the overall shape of the vessel is not lost. This thin plating/coating will also help minimize the overall weight of the system. Maintaining this shape is crucial to ensure the hydrodynamics of the projectile are not negatively affected.

The lack of specified dimensions for the underwater projectiles unfortunately restricts the ability to accurately calculate an estimation for the amount of Galvalum I required to protect the projectiles. Instead, the target lifespan for the sacrificial anode should be determined so that when specifications become available, the necessary amount of Galvalum I can then be calculated. As stated above, the more Galvalum I used as a sacrificial anode, the longer the projectile will be protected. The issue with adding more of the sacrificial anode to the projectile's exterior is the additional weight that comes with it. The additional weight must be kept at a minimum to allow for efficient hydrodynamic travel of the projectile once launched from the host vessel. A compromise between additional protection and minimizing weight must be reached.

Alloy 2507 on its own exhibits excellent corrosion resistant properties in seawater environments. Once the sacrificial anode can no longer offer additional protection after a certain amount of time, the remaining alloy 2507 will still be able to extend the projectile's life span. To maximize the research potential of the projectiles, a target operational lifespan will be set at 3 to 5 years. An ideal design life for the sacrificial anode will be roughly one third of the overall target lifespan of the system. Therefore, the amount of Galvalum I to be used as a sacrificial anode should be capable of protecting the projectile for roughly 1 to 1.67 years. Further studies and calculations will be conducted once dimensional specifications for the projectiles are finalized. This will allow for more accurate design life estimations.

Utilizing a sacrificial anode is a great choice to improve the overall corrosion protection of the projectiles due to the low cost and simplicity of implementation. Galvalum I is the optimal material choice for this anode due to its effectiveness in submerged seawater environments. The overall shape of the projectiles can still be maintained while keeping the additional weight from the anode to a minimum. Although the sacrificial anode will only provide protection for roughly one third of the total operational design life, the excellent corrosion resistant properties of alloy 2507 will continue this protection to extend the life of the projectiles.

Discussion

Maximizing the overall corrosion resistance of the autonomous underwater projectiles has many benefits for the defense industry. The overarching goal of these projectiles is to increase the range of the Navy's research craft. The small projectiles launched from a host vessel are capable of reaching regions in the ocean where larger Navy submarines or ships would risk being detected or logistically could not reach.

Improving the corrosion resistance of the projectiles will greatly extend their operational life cycle. For research purposes, an extended life cycle will allow for longer scientific/surveillance studies and projects to be completed by the Navy, increasing overall Navy intelligence. Due to the great benefits of an extended life cycle, corrosion resistance should be a major focus of this project. The budget spent on the hydrodynamics and autonomous travel of the projectiles should be substantial as it is imperative that the projectiles are able to reach their intended destination to successfully complete their specified mission. This time spent travelling is only a small portion of the overall life of the projectile, however. The projectiles will spend a vast majority of their life stationary and submerged underwater, therefore it would be wise to set aside a sizeable portion of the project's budget solely to improve the projectiles' corrosion resistance in this harsh environment.

One of the goals of this paper was maximize corrosion resistance while minimizing the potential cost. Although alloy 2507 duplex stainless steel tends to be more expensive than other stainless steel alternatives, the metal is still cheaper to implement than many aluminum alternatives while exhibiting superior corrosion resistant properties. A supplemental sacrificial anode plating/coating of Galvalum I is another relatively inexpensive way to improve corrosion resistance without breaking the budget. The only costly process that will be necessary for ensuring optimal corrosion resistance is the high power density welding techniques that will be used for manufacturing the projectiles. Minimizing the cost of corrosion protection will help reduce the overall budget that the Navy will have to spend on this project.

The United States of America as a whole will benefit from any increased capabilities that the Navy will have at their disposal. An increase in Navy intelligence gained from these underwater projectiles will only add to the safety and security of the country. The autonomous capabilities of the projectiles also diminish any risk to Navy personnel. The submarines and ships with crew on board will only be tasked with launching the initial host vessel, therefore the Navy personnel will not be at risk.

Conclusion

The *Methodology for Underwater Deployment from a Host Vehicle* project will benefit greatly from the research conducted on improving the corrosion resistance of the autonomous underwater projectiles. The analysis above focused on selecting the optimal material for maximizing corrosion resistance in a harsh seawater environment and various other additional corrosion protection processes that could be implemented for improved results.

Stainless steel proved to be the best choice of metal when compared with aluminum due to its excellent corrosion resistance characteristics in seawater and high strength properties that would allow the projectile to withstand the heavy pressure loads of the deep sea. Stainless steel is also less expensive than most aluminum alternatives which is an important monetary advantage for the Navy. Alloy 2507 is the ideal duplex stainless steel grade for this application. With a PREN of 43 due to its high chromium and molybdenum content, this metal is excellent for preventing localized pitting and uniform corrosion in seawater environments. The metal's low carbon content also enhances alloy 2507's resistance to carbide-related intergranular corrosion. Crucially, the alloy responds well to heat treatment and exhibits good weldability characteristics that will allow for the metal to be shaped and secured into the desired geometry. The alloy's excellent corrosion resistant characteristics combined with its high strength properties will help extend the operational design life of the underwater projectiles.

Additional corrosion protection processes were also considered to further improve the corrosion resistance of the projectiles. Stainless steels can be susceptible to weld decay which decreases the corrosion resistance of the metal. Welding and heat treatment are two necessary manufacturing processes that must be used to obtain the required cylindrical pressure vessel geometry of the projectile, so mitigating the possibility of weld decay is a necessity. With the use of high power density welding techniques such as laser or electric arc welding, the risk of weld decay occurring to the stainless steel is diminished. Cathodic protection in the form of a sacrificial anode is also another corrosion protection process that should be implemented. The relatively low cost and simplistic installation of the sacrificial anode for the additional corrosion protection make this a great supplementary corrosion protection method. A coating/plating of Galvalum I is the best choice for submerged seawater applications. The projectile will be able to maintain its hydrodynamic shape with a relatively small increase in weight while roughly targeting an additional year of corrosion protection.

Improving the corrosion resistance of the underwater projectiles will extend their operational life cycle, increasing the length of research and surveillance studies available to the Navy. An increase to the Navy's intelligence will benefit the United States as a whole, improving the overall safety and security of the country. This research paper provides a general guideline aimed at maximizing the corrosion resistance of the underwater projectiles. Lacking the dimensional specifics of the projectiles, accurate estimations of overall corrosion resistance, design life and cost of implementation are not currently possible. Once these dimensions are provided for the formal launch of the project in the summer of 2020, this research paper will serve as a useful tool to conduct a deeper, official corrosion analysis of the underwater projectiles.

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