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Coatings for saltwater pipelines

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***Abstract*— *This paper is a literature review of coatings that aim to reduce corrosion in metallic pipelines that are in contact with saltwater. Among the existing coatings, the most common and ecologically available ones are: asphaltic enamel (AE), epoxy resin, Fusion Bonded Epoxy (FBE), Neoprene and multilayer coatings (polyethylene-PE, polypropylene-PP and polyurethane-PU). Due to the need by the industries, new technologies in this field are being developed. Carbon nanotubes, DLC (diamond type carbon), and self-recoating coating are some of the new coatings that are in evidence due to their hydrophobic property. There are many industrial applications that require high resistance to saltwater corrosion, such as coastal factories, onshore and offshore platforms, tidal power plants, and water desalination, which justify researches of new technologies in this area.*

Keywords*— *Coating, Corrosion, Pipeline, Saltwater, Wear.

I. INTRODUCTION

According to Goucher & Walton (2011)[1], since 1800 B.C., iron has been a widely used material for making various types of objects. With the Industrial Revolution in the 19th century, Freeman & Soete (1997)[2] believes that cast iron and steel have gained even more importance in industry. Due to the wide use of these materials and the fact that they are susceptible to corrosion due to the action of salt water, the study of means to avoid this problem has gained relevance.

Corrosion caused by saltwater in contact with metal structure impairs industries located in coastal areas, such as the naval industry, petroleum and gas plants, desalination plants, in addition to thermoelectric and nuclear power plants. All these industries need to protect their metal structures from corrosion by saltwater. In many cases, the use of materials more resistant to corrosion, such as stainless steel, is not enough, so the use of other protection techniques is necessary.

According to the National Association of Corrosion Engineers (2007)[3], the most appropriate and efficient technique for protection against corrosion of pipelines due to saltwater is coating. In this work, some of the most commonly used coating materials will be presented, such as AE, coal tar, epoxy resin, FBE, Neoprene and the multilayer PE, PP and PU coating. There are also new technologies on the market, such as carbon nanotubes, DLC, nanocomposites and self-healing coatings, which are still more expensive.

Due to the wide range of options for coating, one must pay attention to the choice to be made: some of these coatings that are not ecologically correct. Also due account should be taken of the high cost of installation and maintenance of industrial plants that are subject to this environment, which justifies the choice of a suitable coating for each situation.

II. SALTWATER AND WEAR IN METALLIC STRUCTURES

1) SALTWATER

According to Lalli & Parsons (1993)[4] and Narayan, Sharqawy, Lienhard V. & Zubair (2010)[5], saltwater is found mainly in seas and oceans. The measurement of water salinity, according to Lerman (1986)[6] and Libes (1992)[7], is determined by its electrical conductivity, which is related to the amount of dissolved salts.

The salinity is not uniform. It varies between 31 kg / m³ and 39 kg / m³ of dissolved salt, with an average of about 35 kg / m³, according to the location as shown in Figure 1. This variation is due to the different rates of evaporation in the regions of the globe and the addition of fresh water from the polar ice caps. Salinity is also altered with depth: surface water is more saline than deep water, mainly due to interactions between the ocean surface and the atmosphere (Thurman & Burton, 1997)[8].

Saltwater contains more dissolved ions than other types of water and this is the main reason why corrosion is greater in materials in contact with water (Lalli & Parsons, 1993)[9]. Due to the difference in salinity, the composition of salt water is different in each part of the world (Pinet 1996[10], Tavares et al., 2016[11]). This property can be correlated to its corrosion potential.

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Knowing the chemical composition of salt water is essential to define the most suitable pipeline material and coating for each region. In addition to corrosion, one must also take into account the effects of erosion caused by the presence of abrasive particles in water.

The properties of salt water (pH and salinity) and high pressure make the environment very hostile to the operation of metallic underwater equipment. (Frauches-Santos, Albuquerque, Oliveira, & Echevarria, 2014)[12]. The combination of corrosion due to pH and salinity with erosion accelerates the wear of metal structures (Fundão et al., 2017)[13]

2) TYPES OF SALTWATER WEAR

According to Moreno, Bonilla, Adam, Borrachero, & Soriano (2015)[14] and Rodriguez (2018)[15], the main type of corrosion that occurs in saltwater is electrochemical corrosion, shown in Figure 2, which is the conduction of electric current in saltwater, attracting the electrons of the external metal ions, which causes the degradation of the material. There is also anaerobic corrosion, caused by the action of bacteria.

Erosion (Figure 3), according to Anna, Castro, Silva, Franco, & Macêdo. (2008)[16], is a type of wear caused by the repetitive impact of the abrasive fluid against the surface of a solid body. Barber & Motley (2016)[17] also considers as erosion the implosion of bubbles formed in the fluid against the surface of the structure, i.e. cavitation. For Bhushan (2013)[18], this type of wear is generally accelerated by the presence of suspended solid particles.

Another phenomenon that wears metal structures is cavitation, shown in figure 4, which occurs due to high-pressure levels or unstable flows, and can lead to erosion. According to Greenberg (1987)[19] variations in the tides cause variations in the velocity of the currents, causing agitation.

In addition, the deep-sea environment is quite different from the surface. There, there is total absence of sunlight, high hydrostatic pressure and low temperature. These factors must be taken into account in the projects, since it has a great reaction to the wear of metals in contact with saltwater. (Wang, Chen, Chen, Yan, & Xue, 2012[20], Traverso & Canepa, 2014[21]).

III. PIPELINES IN SALTWATER

In the past, pipes were made of materials such as baked clay, wood, stone and cast iron (Antaki, 2003)[22]. Today, there is a wide variety of materials, being the most used steel (carbon or stainless) and PVC (polyvinyl chloride). Many of the applications require resistance to abrasion, cavitation, corrosion and erosion, so often the materials need coating.

Structures in contact with salt water should be designed considering the severe corrosion to which they are subjected. According to Cooper Development Association - CDA (1986)[23] the saltwater pipes are made mainly of stainless steels, uncovered carbon steels, galvanized steels, carbon coated steels, copper alloys, plastics and titanium. Alkazraji (2008)[24], Krauspenhar (2012)[25] and Bahadori (2017)[26] explain that the material of the pipeline must be chosen from the stress and pressure that will be applied to it, since it cannot yield under stress or fail due to fracture initiation. The choice of material must also take into account the weldability and the material manufacturing process.

The pipeline manufacturing area is undergoing changes, both in relation to material and manufacturing processes, as well as in techniques to make them more resistant to the various wear mechanisms that they are exposed to.

For Abdel-Gaber, Abd-El-Nabey, Khamis, & Abd-El-Khalek. (2011)[27] and Sun, Zhang, Liu, & Lu (2012)[28], corrosion is costly and dangerous. The degradation of metallic ducts in contact with salt water leads to a great economic loss and can cause serious environmental accidents without mentioning the extremely toxic substances that are led by them.

IV. EXISTING AND DEVELOPING COATINGS FOR SALTWATER PIPELINES

The coating concept for Grainer & Blunt (1998)[29] is a cover applied to the surface of an object, generally called a substrate, which seeks to alter surface properties such as adhesion, wettability, resistance to corrosion and wear or hardness.

For Byrnes (2017)[30], coating is important in saltwater pipes to increase their corrosion resistance. A coating may be metallic, such as galvanizing, or non-metallic, such as coating with paints. Due to the various types of coating, it is necessary to know the characteristics of each one well in order to apply them when they are most suitable.

The coatings that generate the best results and are currently used most for pipes are Epoxy, FBE, Neoprene, DLC. In the future, these coatings should be replaced by emerging new technologies, such as carbon nanotubes, nanocomposites and self-healing coatings (Yasakau, Tedim, Zheludkevich, & Ferreira., 2014)[31].

1) MOSTLY COMMON COATING TECHNOLOGIES FOR SALTWATER PIPELINES

Fusion Bonded Epoxi (FBE) is one of most common coating technology for satwater pipelines (Wei, Zhang, & Ke, 2007)[32] and features high performance in protecting small and large diameter pipes with moderate operating temperatures. The FBE has excellent adhesion to steel and also provides excellent resistance to cathodic dissociation

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which reduces the cost with cathodic protection during the duct operation (Melot, Paugam, & Roche 2009[33], Nguyen & Martin, 2004[34], Amadi & Ukpaka, 2014[35]). This coating provides physical properties that minimize damage during handling, transport, installation and operation, as well as having good chemical resistance in most soils.

Three-layer polypropylene coating (3LPP) is an anticorrosive system consisting of a high performance FBE followed by a copolymer adhesive and an outer layer of polypropylene. This combination resulted in the most durable and durable coating available on the market a few years ago (Khanna, 2008) [36]. This coating has a strong outer layer that protects the ducts during transportation and installation.

The two-layer PE coating combines a special butyl rubber adhesive with an outer polyethylene coating. The advantages of the coating are resistance to mechanical damage, soil contaminants and cathodic destruction. It can be applied in a temperature range of 241 K to 353 K and in tubes up to 3.5 m in diameter (Suzuki et al., 1986) [37]. The three-layer polyethylene (3LPE) coating is similar to that of two layers, with the addition of a copolymer adhesive, which improves shear properties (Guan, Mayes, Andrenacci, & Wong, 2007) [38]. The performance of the fusion-bonded epoxy coatings can be improved by advanced composite coatings reinforced with nanomaterials (Saliba, Mansur, & Mansur, 2016) [39]. These joint properties provide optimum protection for small and large diameter piping with low temperature flexibility, excellent handling and impact and corrosion resistance.

The neoprene rubber coating consists of a multilayer coating, with a primer bonding agent and an outer layer of polychloroprene. It is usually vulcanized in steel using a steam autoclave, but it can also be applied in place using heated electrical tapes. Provides durable and resistant protection for pipelines and risers with good resistance to absorption of water, hydrocarbons and ozone. (Long, Barnett & High, 1980[40], Runxiu & Jian, 2014[41]).

The modified bitumen AE coating, shown by Mirza, Rasu, & Desilva (2016) [42]. It has been widely used in the corrosion protection of steel pipes. It is a cheap and durable coating. Due to the properties of bitumen, the adhesion to the steel is excellent, which allows a good resistance to corrosion. The main limitation of the coating is in relation to the temperature of the fluid to be transported, which cannot exceed 363 K. AE is a safer and more environmentally friendly system than other similar coatings.

2) NEW TECHNOLOGIES FOR SALTWATER PIPELINES COATING

Vieira (2010) [43] made a study applying carbon nanotubes and titanium dioxide ceramic nanoparticles, added with silver. As a result, he realized that these coatings can minimize corrosion and increase the lifetime of materials submitted to high pressure and temperature during the process of oil extraction in the marine soil.

Diamond-like carbon (DLC) is a very promising coating technology for saltwater pipelines, and has been used for internal coatings in pipelines (Wang et al., 2014) [44]. DLC has disadvantages as a low level of adhesion on the surface of the substrate, which makes it a coat of considerable degradation (Bueno et al., 2018[45]; Liu et al., 2018[46]). However, it is possible to reduce this limitation by deposition of the coating by plasma immersion ionization (PIID).

Ribeiro (2013) [47] did some studies on nanotechnology applied to coatings, with carbon nanotubes (figure 5). The nanotubes are rolled graphene sheets to form a cylindrical structure with a diameter of 1 to 2 nm. Depending on how the graphene sheet is rolled up, the nanotubes may have semi-conductive or metallic properties. According to Ebbesen & Ajayan (1992) [48], these small systems have as physical properties high mechanical resistance and high flexibility, with thermal and electrical characteristics that vary according to the microscopic structure of the tube. In order to produce these nanotubes, we can use the arc discharge method and the laser ablation, under high temperature and chemical vapor deposition (CDV) under low temperature (Larrudé, 2007) [49].

Nanoindentations with epoxy / graphene compounds were investigated by Ribeiro et al. (2015) [50], and showed significant increases in Young's modulus (72%) and hardness (143%), ie the system allows simultaneous gains in the thermal and mechanical properties of the coating.

The problem with all coatings is that they are passive (Costa, Dacoreggio, Kejelin, & Comeli, 2014)[51]. If damaged, no matter how small the damage, the corrosion process begins immediately on the part. The only possible solution to this problem is the use of self-healing material (figure 6), also known as intelligent coating.

These are materials that can partially or totally restore their original functionality after being damaged without any manual intervention (Nazeer & Madkour, 2018)[52]. Some curing agents are isocyanate, epoxy resin, alkyd resin, organic silane and drying oil (Wang et al., 2018)[53].Although the self-healing coating has the curable capability for microcracks, its anti-corrosive performance is far inferior to that of the intact epoxy coating.

There are already uses of self-curing coating along with the epoxy resin. Falcón, Sawczen, & Aoki (2015)[54] describe how to correctly apply the two materials. The self-curable material should be deposited in layers through intelligent nanoreservatories. These tiny

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molecular containers containing corrosion inhibitors are dispersed over the main coating and release the active material in a controlled manner to contain the corrosion reactions in the affected areas and heal the existing damage.

V. ECONOMIC ISSUES INVOLVING SALTWATER PIPELINES

According to Passadore (2013)[55], the costs of corrosive processes in industry are about 3% to 4% of a nation's GDP, which shows the importance of investing in research in this area. These costs can be direct (replacement, repairs, labor, energy, etc.) or indirect costs related to accidents, efficiency, contamination, among others (Oliveira, 2016)[56].

To choose the best type of coating to avoid corrosion, it is necessary to know the characteristics of the environment and the material to be protected (Frauches-Santos, 2013) [57]. The cost and time required to apply the method also should be considered. The most common used solutions to prevent metal corrosion are related to their isolation. Industrial painting, with epoxy-based paints, is one of them. This coating is widely used because of ease of application and maintenance and good cost-effectiveness (Silva, Duarte, & Carvalho, 1998)[58]. By forming a barrier between the metallic substrate and the external medium, industrial paint also results in excellent electrical and chemical behavior in the corrosive environment.

On the other hand, the use of new technologies such as DLC, carbon nanotubes and self-recoverable coating is still small, due to application complexity and cost, but in some high-value applications the investment is already justifiable. In addition, the cost of new technologies tends to fall over time, which can improve the cost-effectiveness of these new coating methods.

VI. FIGURES

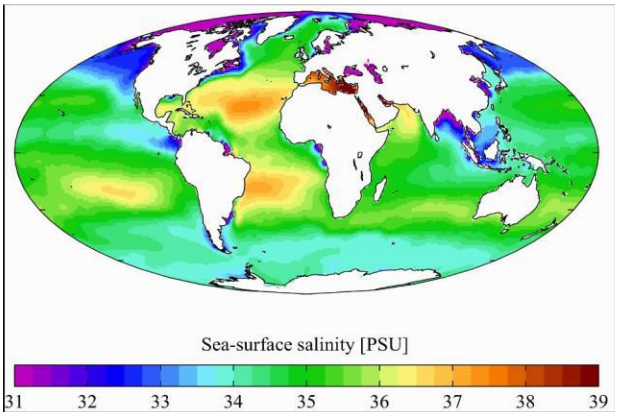

Figure 1: World map with salinity levels of seawater from Narayan et al. (2010)[5].

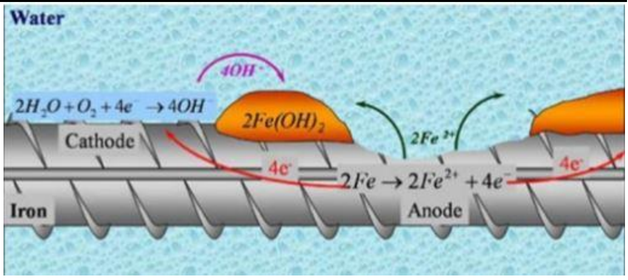

Figure 2: Corrosion mechanism of steel in the sea water. Clear, K.C., Hay, R. E. (1973)[59]

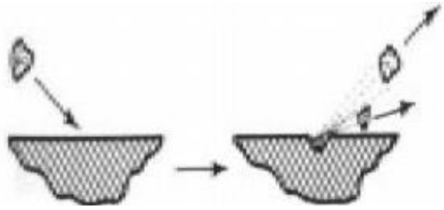

Figure 3: Erosion schema. Mecanismos de desgaste. UNIMAR

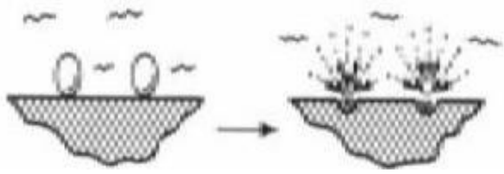

Figure 4: Cavitation schema. Mecanismos de desgaste. UNIMAR.

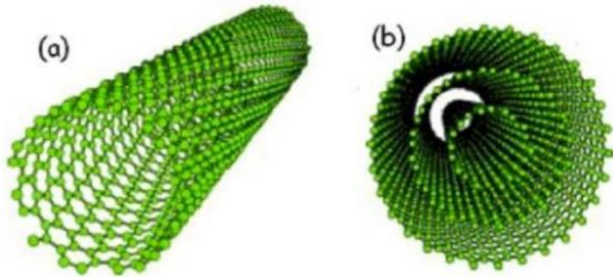

Figure 5: Schematic representation of the structure of carbon nanotubes (a) single wall nanotube, (b) multiple wall nanotube. Zarbin (2007)[60]

Figure 6: Technical concept of self-healing coatings based on microencapsulating healing agents. Andersson, H. M., Wilson, G. (2011)[61]

VII. CONCLUSION

Wear by corrosion on metal pipelines caused by saltwater causes many losses to the world economy. Therefore, research on ways to avoid or minimize this problem is of great importance for the industry, principally those located in coastal regions or that depend on some form of

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salt water, such as onshore, offshore and pre-salt platforms, tidal power plants, nuclear and thermoelectric power plants.

The high investments necessary for the construction of these plants justify the amount spent on coatings to avoid frequent problems with corrosion. Even more technological and expensive coatings, such as DLC, carbon nanotubes, nanocomposites and autocura deserve to have their viability evaluated.

Due to this great industry need, several technologies in this area are being developed, as shown in this literature review. These advances are made to improve the properties of coatings, reducing maintenance costs and risks, and to develop ecologically correct coatings.

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