COATINGS FOR SALTWATER PIPELINES

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Abstract: This paper presents a literature review of coatings applied for saltwater metallic pipelines. The most commonly and environmentally friendly coating techniques available nowadays for pipelines are: Epoxy resin, FBE (Fusion Bonded Epoxy), AE (asphalt enamel), Neoprene and multilayers PE (polyethylene) PP (polypropylene) and PU (polyurethane). This field is growing and new technologies as DLC (diamond-like carbon), carbon nanotubes and self-healing coating are getting an important place to prevent corrosion in metallic components in salted environments due to its hydrophobic property. There are a lot of industry applications that require high resistance to wear due saltwater contact such as tidal power plants, coastal factories, onshore, offshore, pre salt and desalination platforms, etc. Therefore, the study of new technologies in this field is absolutely relevant, and may justify new investments in research and development of smart coatings due to the high installation and maintenance costs related to the industry in saltwater environment, especially in marine environments.

Keywords: Coatings, Pipelines, Saltwater, Wear, Corrosion.

1. INTRODUCTION

The concern with the interaction between saltwater and objects exists since the humanity started to use materials that are susceptible to corrosion, such as cast iron and steel. According to Goucher *et al.* (2011), since 1800 B.C, iron has been used to make objects which in contact with salt water, may be corroded. Freeman *et al.* (1997) believes that with the Industrial Revolution, in early 19th century, there was a large upcoming of cast iron and steel industry and its use was widespread diverse sectors. Due to this facts, the corrosion problem started to become a concern to the whole world, mainly in the fields that have an interaction with saltwater.

Conforming to CDA - Copper Development Association (1986), the corrosion due the saltwater is present in several industrial plants, usually located along the coast. Saltwater may be used for cooling systems, like for thermoelectric and nuclear power plants. Other examples include desalination plants, offshore oil and gas plants, coastal petroleum and petrochemical processing plants, offshore and onshore tidal power plants, and last but not less important the navy application, from ships, and submarines to majors offshore platforms.

All of those industries fields use pipelines in contact with saltwater, and therefore, an efficient and reliable surface protection against corrosion and others types of wear due this contact is crucial. It is used for the corrosion prevention materials less susceptible to the corrosion, such as stainless steel and other kinds of materials, because they are more inert to the corrosion mechanisms. However, using only a material more resistant to the corrosion is not enough to prevent the pipeline wear due its explosion to salted environment. It must be used some kinds of covering technologies to inhibit those phenomena, such as cathodic protection, coatings etc.

The most appropriate technique for pipeline corrosion protection, as reported by National Association of Corrosion Engineers -NACE (2007), is coating, due the fact that some other techniques, like simple painting, are not efficient for pipelines when saltwater is concerned. The complexity of this problem, regarding the water salinity, is discussed along this paper and some special but commonly used coating materials are featured, like Epoxy resin, coal tar, AE, FBE, Neoprene and multilayers PE, PP and PU. There are also new and more expensive technologies such as Carbon nanotubes, DLC, nanocomposites and self-healing coatings. Therefore, there is a range of many kinds of coatings that can be applied to the pipelines surface protection, however, it should be chosen very carefully and one of the reasons to do so is because there are some of these coatings that are not environmentally friendly. Another factor to be taken in consideration is the high cost of installation and maintenance of those industry plants that are subject to this

environment. Thus, researches for the development and large scale manufacturing of new and better coating technologies is much needed, nowadays and according to Petak *et al.* (2017), in his market projection, till 2035.

2. SALTWATER

Water is one of the most abundant substances in earth. According to Laly *et al*. (1993) and Narayan *et al*. (2010), the saltwater is mostly the water from seas and oceans, and its average salinity is about 35 kg/m³. Although the saltwater salinity is mainly between 31 kg/m³ to 39 kg/m³, the seawater is not uniformly saline throughout the whole world, as shown in Fig.1. Lerman (1986) and Libes (1992) show that the salinity measurement is made by determining its electrical conductivity, which is related to the amount of salts dissolved in the water. It is a very important property that may establish some others properties and can be correlated to its corrosion potential. Regions with high evaporation rates present higher salinity indices, while this value tends to decrease in colder areas, due to the fresh water intake from the polar ice caps.

The salinity can still vary depending on the depth. Surface water is more saline than deep water, mainly because of the interactions between the ocean surface and the atmosphere (Thurman, 1997).
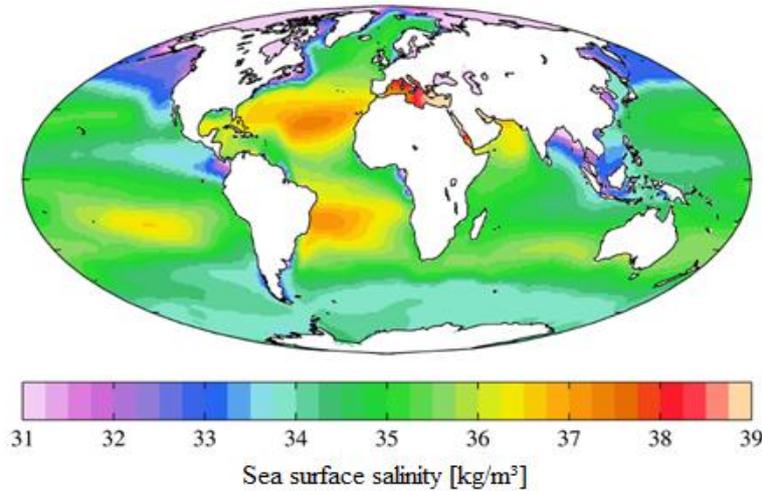

Figure 1: World map with salinity levels of seawater from Narayan *et al.* (2010).

2.1. Saltwater chemical composition

The saltwater contains more dissolved ions than all types of water and that is the main reason why the corrosion is higher on materials in contact with saltwater than with the fresh or pure water (Laly *et al*., 1993). Due to the difference of salinity, the composition of the saltwater is different in each part of the world (Pinet, 1996; Tavares *et al.,* 2016). The average saltwater is compost by the several elements as listed in Tab.1.

Table 1: Saltwater Chemical Composition (Pinet, 1996).

Simb.	Element	Percent
O	Oxygen	85.84
H	Hydrogen	10.82
Cl	Chloride	1.94
Na	Sodium	1.08
Mg	Magnesium	0.1292
S	Sulphur	0.091
Ca	Calcium	0.04
K	Potassium	0.04
Br-	Bromide	0.0067
C	Carbon	0.0028
V	Vanadium	$1.5 \times 10^{-11} - 3.3 \times 10^{-11}$

The chemical composition of the local saltwater is crucial to define the best choice of pipeline materials and coatings. Besides corrosion, it is also important taking into account the effects of other kinds of wear in pipelines, such as erosion, which can be increased by the flow rate and the presence of abrasive particles in the saltwater.

2.2. Wear due to saltwater contact

The wear caused by saltwater contact with metallic structures is a main concern for the pipeline industry. According to Frauches-Santos *et al.* (2013) the saltwater properties make the environment quite hostile to the operation of underwater equipment which are, mostly, exposed to the most extreme conditions such as high pressure, causing abrasion, as well as pH levels and salinity, that can accelerate corrosion. The combined mechanism of corrosion-erosion accelerates the wear in an aqueous environment (Fundão *et al.,* 2017).

According to Singh (2014), corrosion and erosion are distinct processes. Erosion does not apply to electrochemical wear. It can be applied in the case of non-metallic wear. For Anna *et al.* (2008), erosion is a kind of wear by the abrasive action of fluids in motion caused by the repetitive impact of the fluid. Another form of wear, that may be considered erosion, just as Barber *et al.* (2016) present, is the implosion of bubbles formed on fluid against the surface of a solid body, in other words, cavitation. In agreement with Bhushan (2013), this kind of wear is usually accelerated by the presence of suspended solid particles. Zum Ghar (1987) showed that erosion can be classified by: solid particles in fluids; action of liquids; erosion-corrosion; cavitation and thermal erosion.

Rodriguez (2018) and Moreno *et al.* (2015) showed that the main sources of corrosion in saltwater is electrochemical corrosion, as depicted in Fig.2. It consists of the conduction of electrical current in the saltwater, which attracts the electrons of the metal external ions, resulting in the material degradation. Other source of corrosive wear is the anaerobic corrosion, which is caused by the action of bacteria, such as sulphate-reducing bacteria (SRB) that causes metal deterioration. In order to avoid the loss of the pipelines due corrosion, it is commonly used a coating to protect its surface.
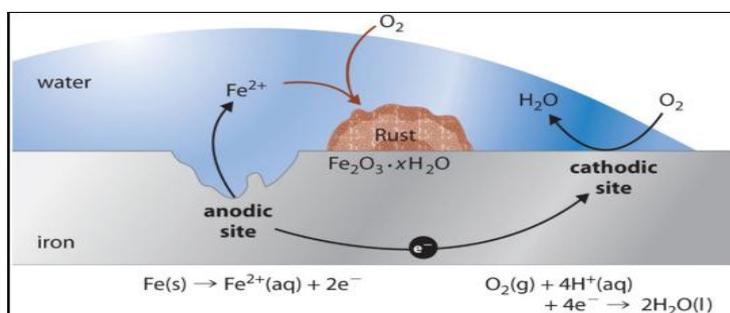

Figure 2: Electrochemical corrosion process from Nazeer *et al.* (2018).

In addition to corrosion, the problem of the proliferation of algae, shellfish and other marine organisms can cause obstruction of the pipes and biological attack on the metal (Kumar *et al.,* 2010).

Cavitation is another phenomenon that my causes wear to pumps and pipelines. It occurs because of high levels of pressure or very unstable flows, and it may lead to erosion. Greenberg (1987) explains that variations in tidal levels cause variations in the speed of the currents, causing more agitation. Faster currents can lead to more erosion. Besides this, the deep sea environment is quite different from the surface, and several conditions like total absence of sunlight, high hydrostatic pressure and a considerable low temperature, are also important in the studies related to the wear of the materials in contact with saltwater (Wang *et al.*, 2012; Traverso *et al.,* 2014).

As reported by Magalhães (2013) and Verichev (2015), abrasive wear in the region of the sea floor (known as "touchdown point", TDP) is one of several challenges that metals are exposed to in an underwater environment. An example is the damage to flexible pipelines that carry oil from the extraction to the floating platform during deep-water oil extraction.

3. SALTWATER PIPELINES

There are a lot of industry applications that require high resistance to saltwater contact, such as tidal power plants, coastal factories, onshore and offshore platforms, etc. Many pipelines and machinery parts demand coatings or some sort of protection against corrosion, erosion, abrasion and cavitation, especially when in contact with saltwater.

According to Antaki (2003), in the past the pipes were made of baked clay, wood, rocks and iron cast, but nowadays they can be manufactured in a wide range of materials, depending on the application. Some examples are carbon steel; ASTM A252 steel pipe; low temperature service carbon steel; stainless steel; non-ferrous metals as cupro-nickel and tantalum lined; and non-metallic, such as tempered glass, Teflon lined, PVC (Polyvinyl chloride) and others.

Just as Tolmasquim (2016) said, for structures with saltwater contact it is important to take in consideration a severe phenomenon that is a challenge: salt promotes an accelerated corrosion. As reported by CDA (1986) the pipes for saltwater are made, mainly, of stainless steels, bare carbon steel, galvanized steel, carbon steel coated, copper alloys, plastics and titanium. Conforming to Alkazraji (2008), Krauspenhar (2012) and Bahadori (2017), the material of the pipeline depends on the stress and pressure that is being applied on it. It cannot yield under stress or fail due to fracture initiation, important property that has to be considered is the mechanical resistance and the weldability. Therefore, other crucial factor to choose the pipeline is its manufacturing process.

The types of tubes are organized by their manufacturing categories. The ones used on offshore installations are known as seamless, submerged arc welded or double submerged arc welded (SAW or DSAW), electric resistance welded (ERW) and spiral weld (Guo *et al.,* 2013). Lee (2008) also describes these three processes as the most usual ones for pipelines' manufacturing. JFE Steel Corporation (n.d.) produces many kinds of tubes, including seamless pipes and columns, cold finished, galvanized, spiral welded pipes etc. Tenaris (n.d.), which is another tubes company, manufactures many kinds of seamless and welded tubes for onshore and offshore line pipe applications. These authors and companies reveal that the manufacturing of pipelines is a field very studied, but is passing through evolutions, not only regarding the material and manufacturing processes, but also takes in consideration a way to make them more resistant to the several mechanisms of wears that they are exposed to.

In the field of power production, for example, tidal turbines work under destructive conditions such as abrasion caused by sand, corrosion because of salinity and high pressure (Lam *et al.,* 2013). According to Winkler (2011), the geological instability can also be a great challenge, like in Himalaya, Andes and Alps, where the water has high concentration of hard mineral particles that cause damage to pipelines and turbine components. To protect the turbine, mainly the moving parts, Lam *et al.* (2013) showed that it is required a high strength low alloy steel (HSLA) with Ni, Cu and Si. Furthermore, Chernin *et al.* (2017), Li *et al.* (2016) and Grogan *et al.* (2013) showed that not only chemical improvements to parts are used for protection, but also the shape of the part itself, like in the case of rotor blades of a turbine. The shape of the blades can prevent cavitation inceptions because of turbulence flow.

The phenomenon of corrosion in oil and gas industry field is mentioned by Olajire (2017), Tolmasquim (2016) and Speight (2014), showing the impacts on its daily activities of drilling rings and production facilities. It is described how parts are affected by corrosion internally and externally. According to Skovhus *et al.* (2017) and Deyab (2018), microbiologically influenced corrosion is also a source of degradation in the oil and gas sector. Therefore, the corrosion control must be part of the daily operation routine.

Migahed *et al.* (2016) showed that the desalination process is another one that presents an issue with saltwater contact. The process itself consists in remove dissolved solids, such as salts and minerals from sea water. This industry is very important because the saltwater is the most traditional and feeding source of water in the world (Kucera, 2014). Due to the fact of desalination plants are mostly made of metallic materials, conforming to Oldfield *et al.* (1997) the corrosion is a great deal to be prevented.

Saltwater is commonly used as thermal fluids in coast factories, where corrosion and erosion by cavitation are present as an enemy factor (Touir *et al.*, 2010).

As reported by Sun *et al.* (2012) and Abdel-Gaber *et al.* (2011), corrosion is not only costly, but dangerous as well, causing a degradation of metallic pipelines at the external or internal surface of the material that has contact with saltwater, which leads to a great economic loss and may cause catastrophic accidents due the hostile and high pressured environment, not mentioning the extremely toxic substances that are extracted of the deep sea soil, as natural gas and petroleum.

4. COATINGS FOR SALTWATER PIPELINES

Coating is important for saltwater pipelines, mainly to increase their corrosion resistance (Byrnes (2017). Galvanizing, for instance, is a kind of coating that is very used for the pipes protection, but there are also some non-metallic coatings, like paint, bitumen, rubber, cement, mortar, etc. Many different types of coating systems and technologies are being released within the past years. It is important understanding them, knowing their properties, how they work and how choosing them properly. According to Grainger *et al.* (1998), coating is a covering that is applied to the surface of an object, usually referred to as the substrate, in order to change the surface properties, such as adhesion, wettability, corrosion resistance, wear resistance or hardness. Smith *et al.* (2004) reported that much progress has been made in the practice of using coating technology to offer corrosion protection to offshore structures and in practically all the structures in contact with the saltwater. For efficient cost saving, these techniques are very important.

The most efficient coatings applied for pipelines nowadays are Epoxy, FBE, Neoprene, DLC and the most emerging technology is pointing out to carbon nanotubes, nanocomposites, and self-healing coatings (Yasakau *et al.,* 2014).

According to Guan *et al.* (2007), pipeline industry uses mastic and copolymers that are two different types of coating adhesives. Recently developed, the two-layer coating system and the three layer polyethylene has greater resistance against impact, lap shear and peel adhesion strength if compared to the less technological coating systems, that conforming to Amadi *et al.* (2014) is coatings such as PU and PE. Based on Moraga *et al.* (2006), polymer blends behave as an electrochemical barrier, as well as a physical barrier that shows corrosion inhibition by improving adhesion to the stainless steel substrate.

Comparing epoxy and solid polyurethanes, the application cost of solids polyurethanes is lower than the epoxy coatings just because of the amount of application each one has, as described by Guan (2001). Following the author's idea, the coating cost is a result of numerous costs and it should cover installation, joint coatings and repairs. Studied by Echeverria (2016), the coating system with epoxy-siloxane topcoat has better performance than the traditional polyurethane topcoat. The author concluded that the impedance module and protective action to the substrate, due to its high resistance to water uptake, is higher with the epoxy-siloxane topcoat. Also a higher concentration of silicon and oxygen increases its corrosion protection.

Another largely widespread technique of coating, described by Dalbin *et al.* (2005), is the chromate anti-corrosive coating. The main point of the authors article is a silica-based coating which is easy to implement, has a lower cost and is as just efficient as the chromate coating.

The reliability of the coatings depends directly on the quality of the treatments applied on the surface and the application procedures (Mirza *et al.,*2016). For saltwater corrosion protection, its quality depends on the well-balanced cycle of four likely important elements: specifying and using a proper coating system, a proper surface preparation for receiving it, a proper application of it, and a quality inspection of it (Guan, 2001). Some other characteristics that provide a good coating for the pipelines are reported by NACE (2007): adherence to pipe, free of defects, pores, flaws, must be an insulating barrier; should be harmless to environment; the coefficient of thermal expansion of the metal should be less than this coefficient of the coating film and the resistance to abrasion and to UV degradation should be high. Besides this, the surface preparation is also important, in order to remove oxides, oil, grease or other contaminants, which can be removed by solvent cleaning or blasting. Samsudin *et al.* (2016), describes how adhesion is optimised by controlling the physical and chemical properties of the adhesive.

4.1. Mostly common coatings technologies for saltwater pipelines

One of the most common coatings technologies for saltwater pipelines is the FBE (Wei *et al.,* 2007). It is a high performance anti-corrosion coating that provides good protection for small and large diameter pipelines with moderate operating temperatures. According to Nguyen *et al.* (2004) and Amadi *et al.* (2014) FBE has excellent adhesion to steel and also provides an excellent resistance to cathodic disbandment which reduces the total cost of cathodic protection during the operation of the pipeline (Melot *et al.,* 2009). This coating provides tough physical properties that minimize damage during handling, transportation, installation and operation and FBE has also been designed for good chemical resistance under most soil conditions.

The three layer polyethylene coating (3LPE), according to Khanna (2008), is a high performance FBE with a copolymer adhesive and an outer layer of polyethylene which adds long lasting protection. Nowadays, it is well known that the performance of fusion-bonded epoxy coatings can be improved through advanced composite coatings reinforced with nanomaterial (Saliba *et al.,* 2016). These properties can be applied to provide a great protection for small and large diameter pipelines. This process has several advantages, like low temperature flexibility, excellent handling, impact resistance and corrosion resistance. Another technology, reported by Guan *et al.* (2007), is the three layer system that uses the copolymer adhesive to guarantee shear properties, combined with the epoxy layer to provide corrosion resistance.

The multi-layer PE coating is another technique that is already known for some decades. It is basically a two-layer corrosion protection system that combines the proven protective qualities of a polyethylene outer coating with a special butyl rubber adhesive. The advantages of this coating are resistance to mechanical damage, resistance to soil contaminants and cathodic destruction, temperature range from 241 K to 353 K and long-term corrosion protection in pipes up to 3.5 m diameter (Suzuki *et al.,* 1984).

The three layer polypropylene coating (3LPP) is also an anti-corrosion system that consists of a high performance FBE followed by a copolymer adhesive and an outer layer of polypropylene which provides the toughest and the most durable pipe coating solution available in the industry by 2008 (Khanna, 2008). One interesting benefit of this technique is the acquirement of tough outer layer of polypropylene that protects the pipelines during transportation and installation, reducing maintenance costs.

More recently, Mirza *et al.* (2016) presented another durable and inexpensive choice of coating, known as AE coating by modified bitumen. It that has been successfully used for corrosion protection of steel pipes and the main benefit consists in an excellent adhesion to steel, due the bitumen properties that provides a track record of long term corrosion resistance. Its main limitation is the temperature of the fluid being transported that cannot exceed 363 K. AE is a much safer and more environmentally friendly system than other similar coatings, like some old ones based on coal tar enamel, which contain carcinogens, as reported by Robinson *et al.* (1984).

The neoprene rubber coating system is another important technology, which consists of a multi-layer coating on a primer bonding agent and an outer layer of polychloroprene that is normally hot-bonded to the steel using a vulcanization process in a steam autoclave. It provides tough, durable protection for pipelines and risers with good resistance to water take-up, hydrocarbons and ozone. It can also be applied as a field joint coating on site, cured using heated electrical tapes (Long *et al.,* 1980 and Runxiu *et al.,* 2014).

Another interesting coating, used to increase the pipeline weight and consequently avoiding buoyancy is the concrete weight coating. According to Subedi (2017) it is recommended to provide negative buoyancy for offshore pipelines, providing resistance against waves, steady currents and corrosion. It is available in various thicknesses and densities, applied by an impinged method, making it ideal for large diameter pipelines, and can have anti-corrosion and insulation coatings applied over it.

4.2. Upcoming coatings technologies for saltwater pipelines

One of the most promising coatings technologies for saltwater pipelines is Diamond-Like Carbon (DLC), which has been used for internal coatings in pipelines (Wang *et al.,* 2014). Even though DLC is a good choice to prevent corrosion, it shows a considerable grade of degradation, (Bueno *et al.,* 2018). Liu *et al.* (2018) reported that DLC

process has some limits for its application because of its low level of adhesion on the substrate surface. But this limitation can be reduced by applying plasma immersion ion deposition (PIID) as a considerable choice of DLC application. As it has a better deposition rate, there is a possibility of applying a thicker layer that can be more conformed to the substrate (Wei, 2010). Costa *et al.* (2011) did an experimental study with a DLC film 20% hydrogenated, showing that it is very effective for the prevention of corrosion under saline solutions.

More recently, important studies have been carried out in nanotechnology applied to coatings. According to Ribeiro (2013), carbon nanotubes are sheets of graphene coiled to form a nearly one-dimensional cylindrical structure with a diameter from 1 to 2nm, as shown in Fig.3. Depending on how the graphene sheet is rolled up, the nanotubes may exhibit metallic or semi conductive properties. Ebbesen *et al.* (1992) reported that this low-dimensional systems exhibits physical properties such as high mechanical strength, high flexibility, electrical and thermal characteristics that can vary significantly depending on the microscopic structure of the tube. Radosavljevic *et al.* (2001) consider that they are the most resistant natural fibers. Some methods have been used for the production of carbon nanotubes, among which three are the main ones: the arc discharge method and the laser ablation, that are both under high temperatures methods and a low-temperature one, chemical vapour deposition (CDV) (Larrudé, 2007).
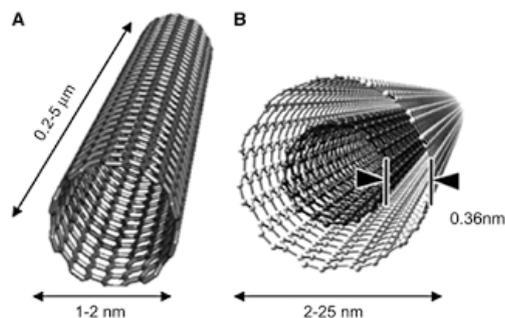

Figure 3: A) Single nanotube, B) Multilayer nanotube, from Mao *et al.* (2017).

Vieira (2010) presented a study applying two types of epoxy tubing coatings, one carbon nanotube attachment and other titanium dioxide ceramic nanoparticles, added with silver. They can minimize corrosion and improve the lifetime of materials and the resistance to high pressure and temperature, during the process of extracting the oil in the sea soil.

Epoxy/graphene based compounds have been investigated for thermal-mechanical performance by Ribeiro *et al.* (2015). These nanoindentation analyses showed significant increases in Young's modulus (72%) and hardness (143%). The system is characterized as multifunctional nanocomposites due to the simultaneous gains in thermal and mechanical properties.

Several new alternatives to corrosion control according to Lopes (2017) are being developed. According to Costa *et al.* (2014), the problem with all the coatings is that they are passive. If the coating itself is damaged, even in a visually imperceptible magnitude, the corrosion process begins to act immediately. According to the authors, the solution may be in an active material, capable of self-healing. It is an important solution that can increase considerably the lifetime of pipelines that is also known as smart coatings.

Self-healing materials are those which can restore nearly or all of its original functionality after being damaged, thus, healed completely or partially. In other words, a self-healing material can detect and automatically heal damage, in other words, the healing process proceeds without any manual intervention (Nazeer *et al.*, 2018). According to Wang *et al.* (2018) various healing agents were proposed for the application of anticorrosive coatings, such as isocyanate, epoxy resin, alkyd resin, organic silane, and drying oil. Among them, drying oil had received much attention due to its sustainable resource, cost effective feature, and autoxidative film forming mechanism. Although the self-healing coating shows an excellent healing ability and corrosion inhibiting function for the microcracks, the anticorrosive performance of the scratched self-healing coating is not comparable with the intact epoxy coating, but they together can create an excellent coating.

The technique requires, according to Falcón *et al.* (2015), the deposition of the protection layer by layer through intelligent nanoreservoirs to increase the performance of active protection systems. These tiny molecular containers, containing corrosion inhibitors that are dispersed over hybrid or organic coatings, offer the release of the active material in a controlled manner, thus being able to contain the corrosion reactions on the affected areas and offering an efficient self-repair ability for the coatings. Wang *et al.* (2018) reported that the efficiency of self-healing coatings can be increased about 6 times by using magnetism. The present work demonstrated the accelerated self-healing activity of magnetic MWCNTs microcapsules in protecting copper surfaces. They present was a very simple and versatile procedure for making magnetic self-healing microcapsules considered to be low cost and suitable for marine engineering.

4.3. Viability of upcoming coatings technologies for saltwater pipelines

The losses caused by corrosive processes are considerably high in the industry. As reported by Passadore (2013), these costs are around 3% to 4% of a nation's GDP, showing that technologies that minimize this process are of vital

economic importance. Corrosion must be analysed through direct costs, which involve replacement, repairs, labour, energy, maintenance, and indirect costs that are relate to accidents, loss of life, quality, efficiency, contamination and, other costs generated by corrosion (Oliveira, 2016).

From previous knowledge of this environment and its characteristics that are responsible for the deterioration of the materials, it is needed the development of methods to combat corrosion Frauches-Santos (2013). This choice depends on the nature of the material to be protected and the salinity level. The cost and the time required to use the method should also be considered. Currently, several anticorrosive techniques have been used, such as coatings, cathodic and anodic protection and corrosion inhibitors. Most of the techniques promote the isolation of the metal from corrosive agents, thus reducing the possibility of corrosion. Silva *et al.* (1998) states that among the existing anticorrosion protection methods, industrial paint, especially epoxy resin paints, is one of the most commonly used techniques, due to its easy application, maintenance and good cost-benefit ratio. As know, the anticorrosive mechanism of this polymeric resin acts as a barrier between the environment and the metal substrate which gives a great electrical and chemical behaviour in corrosive scenery. On the other hand, as Shchukin *et al.* (2006) pointed, even new processes such as self-healing, DLC and nanocomposites, although still very complex and expensive, if taking in consideration the average cost of the damage caused by corrosion, they are very viable, mainly in industrial plants and high value goods, for example, onshore, offshore and pre-salt plants which have an initial pipeline investment around $4500.00 dollars per square meter (Petak *et al.,*2017).

5. CONCLUSION

The study of wear on metallic pipelines, caused by saltwater and the ways to prevent it, is very important to the industry in order to guarantee a longer lifetime and reliable operation. Installations such as tidal power plants, coastal factories, nuclear and thermoelectric power plants, onshore, offshore and pre salt platforms demand high investments, which justify the use of expensive and modern coating materials, such as DLC, carbon nanotubes, nanocomposites and self-healing coatings. The technologies presented in this literature review show how the research in pipeline coatings has been advancing recently, both to provide more environmentally friendly coatings materials, and to get better coatings properties, with a longer lifetime, reducing maintenance costs and risks. Lots of markets which require those technologies are growing, taking for example the petroleum industry and the oil and gas in the USA that, conforming Petak *et al.* (2017), has a projection from 2017 to 2035 to gain $1.06 to $1.34 trillion dollars of investment in that period. If taking into account that this sector is not the only one that is demanding those technologies, it is very clear how new research and development in this field are extremely necessary and motivated by the industry real needs.

6. ACKNOWLEDGEMENTS

7. REFERENCES

Abdel-Gaber, A.M., Abd-El-Nabey, B.A., Khamis, E. and Abd-El-Khalek, D.E., 2011, "A natural extract as scale and corrosion inhibitor for steel surface in brine solution", Desalination, 278(1-3), pp.337-342.
Alkazraji, D., 2008. "A quick guide to pipeline Engineering". Elsevier, 176 p.
Amadi, S.A. and Ukpaka, C.P., 2014, "Performance evaluation of anti-corrosion coating in an oil industry", Int. J. Nov. Res. Eng. Pharm. Sci, 1(03), pp.41-49.
Anna, L. B. S., Castro, P. C. C., Silva, F. J., Franco, S. D., Macêdo, M. C. S., 2008, "Influência do Ângulo de Incidência e da Velocidade de Impacto na Erosão", V Congresso Nacional de Engenharia Mecânica – CONEM.
Antaki, G.A., 2003, "Piping and pipeline engineering: design, construction, maintenance, integrity, and repair", CRC Press, 564 p.
Bahadori, A., 2017, "Oil and gas pipelines and piping systems: design, construction, management, and inspection", Gulf Professional Publishing.
Barber, R.B. and Motley, M.R., 2016, "Cavitating response of passively controlled tidal turbines", Journal of Fluids and Structures, 66, pp.462-475.
Bhushan, B., 2013, "Principles and applications of tribology. John Wiley & Sons", Columbus, USA, 1008 p.
Bueno, A.H.S., Solis, J., Zhao, H., Wang, C., Simões, T.A., Bryant, M. and Neville, A., 2018, "Tribocorrosion evaluation of hydrogenated and silicon DLC coatings on carbon steel for use in valves, pistons and pumps in oil and gas industry", Wear, 394, pp.60-70.
Byrnes, T., 2017, "Pipeline coatings", In Trends in Oil and Gas Corrosion Research and Technologies, pp. 563-591.
Chernin, L. and Val, D.V., 2017, "Probabilistic prediction of cavitation on rotor blades of tidal stream turbines", Renewable Energy, 113, pp.688-696.
Copper Development Association - CDA, 1986, "Materials for Seawater Pipeline Systems: CDA Publication TN38". England: [s.n.]. 14 p.

Costa, R.C., Dacoreggio, M. V., Kejelin, N. Z., & Comeli, F. W., 2014, "Avaliação da resistência a corrosão de revestimentos metálicos depositados por aspersão térmica a arco&58; uma aplicação em trocadores de calor. Soldagem & Inspeção" Vol. 19, 4, pp. 292-301.

Costa, R.P.C., Marciano, F.R., Lima-Oliveira, D.A., Corat, E.J. and Trava-Airoldi, V.J., 2011, "Tribological effect of iron oxide residual on the DLC film surface under seawater and saline solutions", Surface Science, 605(7-8), pp.783-787.

Dalbin, S., Maurin, G., Nogueira, R.P., Persello, J. and Pommier, N., 2005, "Silica-based coating for corrosion protection of electrogalvanized steel", Surface and Coatings Technology, 194(2-3), pp.363-371.

Deyab, M.A., 2018, "Efficiency of cationic surfactant as microbial corrosion inhibitor for carbon steel in oilfield saline water", Journal of Molecular Liquids.

Ebbesen, T.W. and Ajayan, P.M., 1992, "Large-scale synthesis of carbon nanotubes", Nature, 358(6383), p.220.

Echeverría, M., Abreu, C.M., Lau, K. and Echeverría, C.A., 2016, "Viability of epoxy–siloxane hybrid coatings for preventing steel corrosion", Progress in Organic Coatings, 92, pp.29-43.

Falcón, J., Sawczen, T., & Aoki, I. V., 2015, "Uso de nanotubos de haloisita carregados com dodecilamina para aditivação de revestimentos anticorrosivos autorreparadores.", XV Encontro e Exposição Brasileira de Tratamentos de Superfície - EBRATS.

Frauches-Santos, C., Albuquerque, M.A., Oliveira, M.C. and Echevarria, A., 2013, "A corrosão e os agentes anticorrosivos. Revista Virtual de Química", 6(2), Seropédica-RJ, Brazil, pp.293-309.

Freeman, C. and Soete, G., 1997, "Economics of Industrial Innovation", Penguin, Middlesex, 484 p.

Fundão, A.S., da Silva, F.Z., Garcia, D.P., Zancanella, A.C.B., Malheiros, F.C.N., Maziero, R. and da Cunha, V.S., 2017, "Falha por Corrosão em Tubulação de Descarte de Água do Mar". Revista Univap, 22(41), São José dos Campos, Brazil, pp.5-12.

Grainger, S. and Blunt, J., 1998, "Engineering coatings: design and application", Elsevier, Birmingham, United Kingdom, 336 p.

Greenberg, D.A., 1987, "Modeling tidal power". Scientific American, 257(5), pp.128-133.

Grogan, D.M., Leen, S.B., Kennedy, C.R. and Brádaigh, C.Ó., 2013, "Design of composite tidal turbine blades", Renewable Energy, 57, pp.151-162.

Guan, S., 2001, "Corrosion protection by coatings for water and wastewater pipelines", Appalachian Underground Corrosion Short Course, Water and Wastewater Program, West Virginia University, PA, 28 p.

Guan, S., Mayes, P., Andrenacci, A. and Wong, D., 2007, "Advanced two layer polyethylene coating technology for pipeline protection", In International Corrosion Control Conference, Sydney, Australia.

Guo, B., Song, S. and Ghalambor, A., 2013, "Offshore pipelines: design, installation, and maintenance", Gulf Professional Publishing, Lafayette, USA, 400 p.

JFE Steel Corporation, n.d., "Speciality Pipe and Tube for Boiler and Petrochemical Plant", JFE Steel Corporation, Japan, 25 p.

Khanna, A.S. ed., 2008, "High-performance organic coatings", Elsevier, Boca Raton, USA, 472 p.

Krauspenhar, T.L., 2012, "Avaliação da resistência à corrosão-fadiga do aço API 5CT P1 10 em meio aquoso salino contendo H2S", Porto Alegre, Brazil, 109 p.

Kucera, J. ed., 2014, "Desalination: water from water", John Wiley & Sons, New Jersey, USA, 664 p.

Kumar, P. and Saini, R.P., 2010, "Study of cavitation in hydro turbines—A review". Renewable and Sustainable Energy Reviews, 14(1), pp.374-383.

Laly, C.M. and Parsons, T. R., 1993, "Biological Oceanography – An introduction". Eds. Butterworth Heinemann, University of British Columbia, Vancouver, Canada, 320 p.

Lam, W.H. and Bhatia, A., 2013, "Folding tidal turbine as an innovative concept toward the new era of turbines", Renewable and Sustainable Energy Reviews, 28, pp.463-473.

Larrudé, D.R.G., 2007, "Nanotubos de carbono decorados com partículas de cobalto", Pontifícia Universidade Católica, PUC, Rio de Janeiro, Brazil, 103 p.

Lee, J., 2008, "Introduction to offshore pipelines and risers", 182 p.

Lerman, M., 1986, "Marine Biology. Environment, Diversity and Ecology", The Benjamin/Cummings Publishing Company, Inc. Eds, 520 p.

Li, W., Zhou, H., Liu, H., Lin, Y. and Xu, Q., 2016, "Review on the blade design technologies of tidal current turbine", Renewable and Sustainable Energy Reviews, 63, pp.414-422.

Libes, S., 2011, "Introduction to marine biogeochemistry", Academic Press, 928 p.

Liu, L., Wu, Z., An, X., Xiao, S., Cui, S., Lin, H., Fu, R.K., Tian, X., Wei, R., Chu, P.K. and Pan, F., 2018, "Excellent adhered thick diamond-like carbon coatings by optimizing hetero-interfaces with sequential highly energetic Cr and C ion treatment", Journal of Alloys and Compounds, 735, pp.155-162.

Long, D.D., Barnett, G.A. and High, G.M., Lowenstein Corp, 1980, "Neoprene coating composition for reinforcement fabrics for rubber products, process, and products produced thereby", U.S. Patent 4,205,559, Jun. 3, 1980, 8 p.

Lopes, N. F., 2017, "Corrosão de aços utilizados na indústria de petróleo por CO2 sob pressão, temperatura e meio corrosivo similar ao encontrado em reservatórios do Pré-sal", Porto Alegre, Brazil, 121 p.

Magalhães, L.D.R., 2013, "Desenvolvimento e fabricação de penetradores para avaliação da resistência ao desgaste abrasivo de polímeros protetores de risers", Uberlândia, Brazil, 144 p.

Mao, B., Calatayud, D. G., Mirabello, V., Kuganathan, N., Ge, H., Jacobs, R. M., & Botchway, S. W., 2017, " Fluorescence Lifetime Imaging and Super Resolution Microscopies Shed Light on the Directed and Self Assembly of Functional Porphyrins onto Carbon Nanotubes and Flat Surfaces.", Chemistry-A European Journal, Vol. 23, 41, pp. 9772-9789.

Mélot, D., Paugam, G. and Roche, M., 2009, "Disbondments of pipeline coatings and their effects on corrosion risks", Journal of Protective Coatings & Linings, p.18.

Migahed, M.A., Rashwan, S.M., Kamel, M.M. and Habib, R.E., 2016, "Synthesis, characterization of polyaspartic acid-glycine adduct and evaluation of their performance as scale and corrosion inhibitor in desalination water plants", Journal of Molecular Liquids, 224, pp.849-858.

Mirza, M., Rasu, E. and Desilva, A., 2016, "Surface Coatings on Steel Pipes Used in Oil and Gas Industries-A Review", American Chemical Science Journal, 13.

Moraga, G.A., Silva, G.G., Matencio, T. and Paniago, R.M., 2006, "Poly (2, 5-dimethoxy aniline)/fluoropolymer blend coatings to corrosion inhibition on stainless steel", Synthetic metals, 156(16-17), pp.1036-1042.

Moreno, J.D., Bonilla, M., Adam, J.M., Borrachero, M.V. and Soriano, L., 2015, "Determining corrosion levels in the reinforcement rebars of buildings in coastal areas. A case study in the Mediterranean coastline", Construction and Building Materials, 100, pp.11-21.

Narayan, G.P.; Sharqawy, M.H.; Lienhard V, J.H.; Zubair, S.M., "Thermodynamic Analysis of Humidification Dehumidification Desalination Cycles". Desalination and Water Treatment 2010, 16 p., 339–353.

National Association of Corrosion Engineers, 2007, "NACE Standard RP0169-2007. Control of External Corrosion on Underground Or Submerged Metallic Piping Systems". NACE, 36 p.

Nazeer, A.A. and Madkour, M., 2018, "Potential use of smart coatings for corrosion protection of metals and alloys: A review", Journal of Molecular Liquids.

Nguyen, T. and Martin, J.W., 2004, "Modes and mechanisms for the degradation of fusion-bonded epoxy-coated steel in a marine concrete environment", JCT research, 1(2), pp.81-92.

Olajire, A.A., 2017, "Corrosion inhibition of offshore oil and gas production facilities using organic compound inhibitors-A review". Journal of Molecular Liquids.

Oldfield, J.W. and Todd, B., 1997, "Environmental aspects of corrosion in MSF and RO desalination plants", Desalination, 108(1-3), pp.27-36.

Oliveira, A.R.D., 2016, "Corrosão e tratamento de superfície." Instituto Federal De Educação, Ciência E Tecnologia Belém – Pa

Passadore, J.D.A., 2013, "Estudo e caracterização de filmes hidrofóbicos e sua utilização como tratamento anticorrosivo para metais", Universidade de São Paulo, 132 p.

Petak, K., Vidas, H., Manik, J., Palagummi, S., Ciatto, A. and Griffith, A., 2017, "U.S. Oil and Gas Infrastructure Investiment Through 2035: An Engine For Economic Growth", [online] Washington, USA: American Petroleum Institute, 159 p. Available at: http://www.api.org/~/media/Files/Policy/Infrastructure/API-Infrastructure-Study-2017.pdf [Accessed 19 Mar. 2018].

Pinet, P.R., 1996, "Invitation to Oceanography", West Publishing Company, USA, 508 p.

Smith, C., Siewert, T., Mishra, B., Olson, D., and Lassiegne, A., 2004, "NIST Special Publication 1035. Coatings for Corrosion Protection: Offshore Oil and Gas Operation Facilities, Marine Pipeline and Ship Structures ", Biloxi, USA, 334 p .

Radosavljević, M., Lefebvre, J. and Johnson, A.T., 2001, "High-field electrical transport and breakdown in bundles of single-wall carbon nanotubes", Physical Review B, 64(24), p.241307.

Ribeiro, H., da Silva, W.M., Neves, J.C., Calado, H.D.R., Paniago, R., Seara, L.M., das Mercês Camarano, D. and Silva, G.G., 2015, "Multifunctional nanocomposites based on tetraethylenepentamine-modified graphene oxide/epoxy", Polymer Testing, 43, pp.182-192.

Ribeiro, L.D., 2013, "Aplicação de Nanotubos de Carbono Verticalmente Alinhados em Membranas de Separação Entre Água e Óleo", São José dos Campos, Brazil, 131 p.

Robinson, M., Buii, R.J., Munch, J. and Meier, J., 1984, "Comparative carcinogenic and mutagenic activity of coal tar and petroleum asphalt paints used in potable water supply systems", Journal of applied toxicology, 4(1), pp.49-56.

Rodriguez, B., 2018, "The Effects of Saltwater on Metals". Disponível em: <https://sciencing.com/effects-saltwater-metals-8632636.html>. Acessed in: 10 nov. 2017.

Runxiu, W., Jian, Z., 2014, "Two-component neoprene coating", Chinese Patent CN103525304, Jan. 22 2014, 4 p.

Saliba, P.A., Mansur, A.A. and Mansur, H.S., 2016, "Advanced Nanocomposite Coatings of Fusion Bonded Epoxy Reinforced with Amino-Functionalized Nanoparticles for Applications in Underwater Oil Pipelines", Journal of Nanomaterials, 2016, p.29.

Samsudin, M.S.F., Dell'Olio, M., Leong, K.H., Ahamid, Z. and Varley, R.J., 2016, "Adhesives performance of 3-layer PE pipe coatings: Effects of MAH loading, PE particles size, coating interval time and service temperature" Progress in Organic Coatings, 99, pp.157-165.

Shchukin, D.G., Zheludkevich, M., Yasakau, K., Lamaka, S., Ferreira, M.G., & Möhwald, H., 2006, "Layer-by-Layer assembled nanocontainers for self-healing corrosion protection.", Advanced Materials, Vol. 18, 13, pp. 1672-1678.

Silva, M. L., Duarte, M. S. C., & de Carvalho, G. L., 2016, "Tratamento Anticorrosivo da Superfície Interna em Tanques de Armazenamento de Derivados do Petróleo com Resina Epóxi.", Revista Científica Semana Acadêmica, 11 p.

Singh, R., 2014, "Corrosion Control for Offshore Structures: Cathodic Protection and High-Efficiency Coating", Gulf Professional Publishing, USA, 254 pages.

Skovhus, T.L., Eckert, R.B. and Rodrigues, E., 2017, "Management and control of microbiologically influenced corrosion (MIC) in the oil and gas industry—Overview and a North Sea case study", Journal of biotechnology, 256, pp.31-45.

Speight, J.G., 2014, "Oil and Gas Corrosion Prevention: From Surface Facilities to Refineries", Gulf Professional Publishing, Wyoming, USA, 150 p.

Subedi, R., 2017, "Finite Element Analysis of a Subsea Pipeline Behavior within its Concrete Weight Coating", Memorial University, DOI:10.13140/RG.2.2.23008.69125.

Sun, J.B., Zhang, G.A., Liu, W. and Lu, M.X., 2012, "The formation mechanism of corrosion scale and electrochemical characteristic of low alloy steel in carbon dioxide-saturated solution", Corrosion Science, 57, pp.131-138.

Suzuki, K., Ishida, M., Ohtsuki, F., Inuizawa, Y., Hinenoya, S., Tanaka, M. e Shindou, Y., "Polypropylene Coated Steel Pipe", US Pat. 4,606,953, Aug. 19 1986, 13p.

Tavares, S.S.M., Pardal, J.M., Mainier, F.B., Da Igreja, H.R., Barbosa, E.S., Rodrigues, C.R., Barbosa, C. and Pardal, J.P., 2016, "Investigation of the failure in a pipe of produced water from an oil separator due to internal localized corrosion", Engineering Failure Analysis, 61, pp.100-107.

Tenaris, n.d., "Offshore and Onshore Pipeline Solutions", 11 p.

Thurman, H.V. and Burton, E.A., 1997, "Introductory Oceanography", New Jersey: Prentice Hall, New Jersey, USA, 544 p.

Tolmasquim, M.T., 2016, "Energia renovável: hidráulica, biomassa, eólica, solar, oceânica", EPE: Rio de Janeiro.

Touir, R., Dkhireche, N., Touhami, M.E., Sfaira, M., Senhaji, O., Robin, J.J., Boutevin, B. and Cherkaoui, M., 2010, "Study of phosphonate addition and hydrodynamic conditions on ordinary steel corrosion inhibition in simulated cooling water", Materials Chemistry and Physics, 122(1), pp.1-9.

Traverso, P. and Canepa, E., 2014, "A review of studies on corrosion of metals and alloys in deep-sea environment", Ocean Engineering, 87, pp.10-15.

Verichev, S.N., Mishakin, V.V., Nuzhdin, D.A. and Razov, E.N., 2015, "Experimental study of abrasive wear of structural materials under the high hydrostatic pressure", Ocean Engineering, 99, pp.9-13.

Vieira, A.M., "Nanotecnologias da UFMG devem reforçar vida útil de dutos da Petrobras" Boletim UFMG, Belo Horizonte, Brazil, n. 1723, dez. 2010. Available at: <https://www.ufmg.br/boletim/bol1723/5.shtml>. Accessed in: 11 mar. 2018.

Wang, H. and Zhou, Q., 2018, "Evaluation and failure analysis of linseed oil encapsulated self-healing anticorrosive coating" , Progress in Organic Coatings, 118, pp.108-115.

Wang, J., Chen, J., Chen, B., Yan, F. and Xue, Q., 2012, "Wear behaviors and wear mechanisms of several alloys under simulated deep-sea environment covering seawater hydrostatic pressure", Tribology International, 56, pp.38-46.

Wang, W., Li, W., Fan, W., Zhang, X., Song, L., Xiong, C., Gao, X. and Liu, X., 2018, "Accelerated self-healing performance of magnetic gradient coating", Chemical Engineering Journal, 332, pp.658-670.

Wang, Z.M., Zhang, J., Han, X., Li, Q.F., Wang, Z.L. and Wei, R., 2014, "Corrosion and salt scale resistance of multilayered diamond-like carbon film in CO2 saturated solutions", Corrosion Science, 86, pp.261-267.

Wei, R., 2010, "Development of new technologies and practical applications of plasma immersion ion deposition (PIID)", Surface and Coatings Technology, 204(18-19), pp.2869-2874.

Wei, Y.H., Zhang, L.X. and Ke, W., 2007, "Evaluation of corrosion protection of carbon black filled fusion-bonded epoxy coatings on mild steel during exposure to a quiescent 3% NaCl solution", Corrosion science, 49(2), pp.287-302.

Winkler, K., 2011, "Coating for sustainable turbine parts", Hydro News – Magazine of Andritz Hydro, No. 21, pp. 4-6.

Yasakau, K.A., Tedim, J., Zheludkevich, M.L., Ferreira, M.G.S., 2014, "10 - Smart self-healing coating for corrosion protection of aluminium alloys", in: Makhlouf, A.S.H. (Ed.), "Handbook of smart coatings for materials protection (No. 64)", Edinburg, United States, Elsevier, 656 p. "Handbook of Smart Coatings for Materials Protection", Woodhead Publishing Ltd, UK, Pages 224–274.

Zum Gahr, K.H., 1987, "Microstructure and wear of materials", Vol. 10, Elsevier, Karlsruhe, Germany, 559 p.

8. AUTHOR RESPONSIBILITY

The authors are the only ones responsible for the content of this paper.