A Review on Deterioration of Mechanical Behaviour of High Strength Materials under Corrosive Environment

Sunil Kumar S1*, Neelakantha V Londe2, Dilip Kumar K3, Md. Ibrahim Kittur4

1 Research Scholar, Dept. of Mechanical Engineering, MITE, Moodabidri, Karnataka, INDIA.
2 Professor, Dept. of Mechanical Engineering, MITE, Moodabidri, Karnataka, INDIA.
3 Professor, Dept. of Mechanical Engineering, SDIT, Mangalore, Karnataka, INDIA.
4 Assistant Professor, Dept. of Mechanical Engineering, PACE, Mangalore, Karnataka, INDIA.

*Corresponding Author: sunilgooch@gmail.com, sunilkumar@mite.ac.in

Abstract. Surface corrosion has a major influence on ageing of high strength materials that leads to degradation in mechanical properties. Therefore, design of a component frequently implores the engineer to minimize the possibility of failure particularly by environmental deterioration. Effect of corrosive environment on high strength materials of Aluminum alloys and steels is studied. The influence of corrosion on material loss and deprivation of mechanical behaviour such as ultimate strength, yield strength and fatigue resistance are reviewed and presented. Salt spray test as per ASTM B117 and immersion in natural sea water are the usual practices followed to induce corrosion. It is evident from the literatures that corrosion has a significant effect on deterioration of mechanical behaviour of the materials.

Keywords: Corrosion, High strength materials, Mechanical behaviour.

1. Introduction

Engineering materials during their service life are exposed to mechanical failure due to major causes such as fracture, fatigue, creep, wear and corrosion. Materials do not reach their theoretical strength when tested practically. Therefore, the performance of the material in service is not same as expected. Hence, the design of a component frequently implores the engineer to minimize the possibility of failure particularly by environmental deterioration such as corrosion. It could be found that the concentration of chloride is more in offshore or marine environment that leads to chloride induced corrosion, a key cause of deterioration of structural materials such as steel. The effect of corrosion on structural materials in service life leads to mechanical failure [1, 2, 3]. The structural Steel bars in reinforced concrete must possess high tensile strength because they are usually subjected to tensile loads. Therefore, the corrosion of the reinforcing steel bars in concrete is primary cause for failure of concrete structures [4, 5]. The present days standards have led the structural steels to have load carrying capacity with respect to fatigue load that varies with time. However, a little work has been done on effect of corrosion on low cycle fatigue of structural steels.

The fatigue load on the structures causes sudden cracks on the surface which breaks the oxide layer and thus enhancing faster corrosion rate when compared with static loads [6-15]. Rain, fog and condensation due to temperature change are the causes for the formation of electrolytic layer on the
metal surface which results in atmospheric corrosion. The chlorides in the coastal region increases the conductivity of electrolytic film on the metals and tries to destroy the passivity, which is a cause for increase in corrosion rate [16-82]. Atmospheric corrosion monitoring sensors are used to measure the cause and property of electrolytic film [17]. Structural steels used in harbours, shipping, sheet piling will generally have cathodic protection which is effective only if properly maintained for a certain time period. However, some structures not only depend on time but there are other crucial parameters such as temperature, microbiological nutrients such as dissolved inorganic nitrogen by which the coated surfaces are also induced with corrosion thus leading to failure of the structures [18]. Corrosion results in failure of structures, leakages in pipelines, contamination of the environment which may me trivial but finally leads to loss of life at higher degree of occurrence [19]. Thus, it is evidenced from the literatures that corrosion is a vital reason for deterioration of marine and off shore structures.

2. Salt Spray Test
An extensive research is in development to identify the effect of salt spray on metallic materials such as steels, magnesium alloys and aluminum alloys. Charis A. Apostolopoulos has examined the effect of corrosion on mechanical performance of B500c steel bars. The tensile specimens are immersed in salt spray chamber for a period of up to 120 days as per ASTM B117 [15] specifications [67]. The salt solution contains 5 % of NaCl in 95 % of distilled water with a pH range of 6.5 to 7.2 and the temperature in the salt chamber is about 35 °C [15]. The mass loss is found to be linear with respect to time of exposure with about 14 % of mass lose at the exposure time of 120 days. Increasing tendency of reduction in yield strength and ultimate tensile strength is observed. At the end of 120 days of exposure, the yield strength and the ultimate strength are reduced by 32 % and 23 % respectively [1] as shown in the Fig.1.

![Fig.1: Influence of exposure time on yield stress and ultimate stress](image)

Experiments have been carried out to find the effect of salt spray on reinforcement steel bars of BSt 420 as per ASTM B117 [67]. There is increasing tendency of decrease in mass, yield stress, ultimate stress and elongation at failure with increase in exposure time [2]. Three forms of corrosion such as general, pitting and filiform are quantified by optical microscopy, laser profilometry and SEM on the material of extruded AM30 magnesium alloy. Both salt spray and immersion test have been carried for a period of about 60 hours. It is observed that immersion has higher influence on general and pitting corrosion whereas filiform corrosion is more in salt spray environment [3]. Reinforcing steel bars of S500 and B500 are tested for their tensile strength after exposure in corrosive atmosphere of artificial salt spray chamber. There is reduction in mass of both the materials and thus the diameter of the
tensile specimens is decreased with increase in exposure time. It is observed that there is decrease in yield stress and ultimate stress which is displayed in Fig.2. Elongation at fracture and strain energy density are also found to decrease with increase in exposure time [4]. The effect of salt spray on low cycle fatigue behaviour of S500 steel bars is presented. The alternating load of low cycle fatigue has resulted in formation of surface cracks which affected the oxide layer and resulted in faster corrosion rate. It is observed that there is gradual reduction in both loadbearing ability and available energy and also proved the reduction in the ductility of the material [6]. The evaluation of corrosion is usually made by weight loss of the material [1-15].

3. Atmospheric Corrosion

Research is under evolution on the atmospheric corrosion particularly in coastal regions. This type of corrosion is not accelerated as in case of salt spray chamber, but it is more significant due to naturality. Atmospheric corrosion is the result of chlorides of aqueous precipitation such as fog, salinity in marine environment, precipitation of dew due to humidity change. These chlorides adhere to the metal surface and results in corrosion [7-82]. Rate of atmospheric corrosion can also be monitored in a short span of time by using corrosion monitoring sensor which works on galvanic current rather than exposure for a longer time [16]. The rate of corrosion in structural steels in sea water is increased by nutrient concentration such as dissolved inorganic nitrogen. It is predicted that at elevated nutrient concentrations which can be equalized with pollution of sea water, corrosion losses are determinably higher when compared with nonpolluted sea water [17]. The passive layer on the material surface breaks down at some localized points, referred to as pitting corrosion of marine and offshore steels structures. The cause for pitting, pitting depth analysis and related mathematical relationships are primary factors to be considered [18].

Jyoti Bhandari et al [19] has reviewed the literatures on pitting corrosion to identify and evaluate the parameters that affect pitting corrosion in off shore and marine environments and has depicted that pitting is one of the most destructive corrosions and the various factors which affect the pitting corrosion are atmosphere, temperature, pH level, splash etc. However, there are less attempts made on probability modelling for corrosion as a function of time in the recent years.
The materials of aircraft structures likewise degrade under corrosion. Pantelakis et al. [20] have evaluated the tensile behaviour of high strength aluminum alloys of 2024, 8090, 2091 and 6031 after corrosion. Mechanical degradation is observed proving decrease in yield strength and ultimate strength with enhanced intergranular cracking when exposed to longer time. However, there is noticeable volumetric embrittlement at lesser exposure time. Corrosion also has a significant effect on wear characteristics of materials [33, 34]. The authors have examined the various behaviour of corroded materials with respect to time of exposure [21 – 82]. In this way corrosion of high strength materials is an extensive topic that researchers are working on, but the evaluation of mechanical degradation of materials due to marine chloride is an emerging research study.

4. Influence of corrosion on fracture properties

Fracture mechanics is the branch of solid mechanics which explains the mechanical behaviour of bodies having cracks under different loading conditions. The past experience of structural failures and the desire for increased safety and reliability of mechanical systems like automobiles, aero planes, bridges, pipelines, pressure vessels and components of nuclear plants etc. have led to the development of different fracture criteria. Fracture Mechanics deals with the fracture properties of the above said structural materials under corrosive environments. It is concerned with the study of the initiation and propagation of cracks. The fracture properties such as fracture toughness, fatigue crack growth rate and threshold stress intensity factor are important material properties considered in machine design based on fracture Mechanics [83-103]. Research is under advancement for predicting the failure of structural materials by the mechanism of Stress Corrosion Cracking (SCC).

Iliyasu I et al. [83] have studied the susceptibility of austenitic stainless steel to stress corrosion cracking in sodium chloride. The stress corrosion cracking (SCC) behaviour of type 304 austenitic stainless steel in Sodium Chloride (NaCl) has been investigated. This was done by exposing the entire specimen to the corrosives (NaCl) at concentrations of 0.3M, 0.5M, 0.7M, and 1M. After every seven days one specimen from each of these corrosives is removed and loaded on a tensometer until fracture. Percentage elongation and percentage reduction in cross sectional area are used to investigate the SCC behaviour of the steel. The ductility of Type 304 Austenitic stainless steel decreased with increased exposure time and concentration.

Gamboni et al. [84] have studied the effect of salt-water fog on fatigue crack nucleation of Al and Al-Li alloys. Fatigue and corrosion-fatigue tests are performed to quantify the fatigue properties of AA2524-T3 and AA2198-T851 Al alloys. High cycle axial fatigue tests are carried out under air and salt-water fog conditions. The results indicate that the saline environment has a deleterious effect on the fatigue life of aluminum alloys.

Samir Milad Elsariti et al [85] have studied the behaviour of stress corrosion cracking (SCC) of austenitic stainless steels of types 316 is investigated as a function of applied stress at room temperature in sodium chloride solutions using a constant load method. There is a high susceptibility of SCC on failure of the material.

SCC is characterized by synchronised action of stresses and corrosion effect and is one of the principal failures of the structures particularly in marine environment which causes catastrophic rupture and thus leads to economic losses [103]. Generally, the surface of the material is susceptible to SCC because of chloride concentration. It is evident from the literatures that materials such as structural
steels have experienced failure due to SCC in marine environment [83-103]. However, the SCC mechanism and the study of fracture mechanics due corrosion needs further investigation.

5. Conclusion
There are several literatures that explains about the influence of corrosion on the mechanical behaviour of the high strength materials such as structural steels. This article reviews the identification of various conventional and recent methods to model the corrosion and its effects. It is obvious from the literature that there are appropriate methods such as salt spray test as per the ASTM standards B117 to perform corrosion test on the materials and thus recon the rate of corrosion. It is also evident that the corrosion tests can be performed by immersing the specimens of the materials in natural sea water. The following conclusions could be presented from the literatures.

- The factors that influence the corrosion are temperature, pH, time, rain, fog, micro biological nutrients such as dissolved inorganic nitrogen, salinity, humidity etc.
- The chlorides in the coastal region increases the conductivity of electrolytic film on the metals and tries to destroy the passivity, which is a cause for increase in corrosion rate that leads to chloride induced corrosion, a key cause of deterioration of structural materials such as steel.
- The literatures on salt spray test has proved that the corrosion strongly affects the mechanical properties of structural materials. It is manifested that there is increasing tendency of decrease in mass, yield stress, ultimate stress and elongation at failure with increase in exposure time. There is gradual reduction in both load bearing ability and available energy and also reduction in the ductility of the material.
- The literatures on stress corrosion cracking (SCC) prove that the structural steels have very high susceptibility for SCC in marine environment and the materials exhibit brittle failure under prematured crack growth. The fracture strength of the corroded specimens is drastically decreased due to pitting corrosion which is a key influence for early fatigue crack growth initiation.
- However, the SCC mechanism and the study of fracture mechanics due to corrosion needs further investigation. The detailed study of fracture parameters such as threshold stress intensity factor, fatigue crack growth, fracture toughness, stress triaxiality, crack tip opening displacement etc of the structural materials after sea water immersion which is equivalent to corrosion in marine environment could be considered as the future scope of this study.

References

[1] Apostolopoulos, C.A., Demis, S. and Papadakis, V.G., 2013. Chloride-induced corrosion of steel reinforcement–Mechanical performance and pit depth analysis. Construction and Building Materials, 38, pp.139-146.
[2] Apostolopoulos, C.A. and Papadakis, V.G., 2008. Consequences of steel corrosion on the ductility properties of reinforcement bar. Construction and Building Materials, 22(12), pp.2316-2324.
[3] Song, W., Martin, H.J., Hicks, A., Seely, D., Walton, C.A., Lawrimore II, W.B., Wang, P.T. and Horstemeyer, M.F., 2014. Corrosion behaviour of extruded AM30 magnesium alloy under salt-spray and immersion environments. Corrosion Science, 78, pp.353-368.
[4] Papadopoulos, M.P., Apostolopoulos, C.A., Alexopoulos, N.D. and Pantelakis, S.G., 2007. Effect of salt spray corrosion exposure on the mechanical performance of different technical class reinforcing steel bars. Materials & design, 28(8), pp.2318-2328.
[5] Apostolopoulos, C.A., Papadopoulos, M.P. and Pantelakis, S.G., 2006. Tensile behavior of corroded reinforcing steel bars BSt 500s. Construction and building Materials, 20(9), pp.782-789.
[6] Apostolopoulos, C.A., 2007. Mechanical behavior of corroded reinforcing steel bars S500s tempcore under low cycle fatigue. Construction and Building Materials, 21(7), pp.1447-1456.
[7] Gonzalez, J.A., Feliu, S., Rodriguez, P., Ramirez, E., Alonso, C. and Andrade, C., 1996. Some questions on the corrosion of steel in concrete—Part I: when, how and how much steel corrodes. Materials and structures, 29(1), p.40.

[8] Batis, G. and Rakanta, E., 2005. Corrosion of steel reinforcement due to atmospheric pollution. Cement and concrete composites, 27(2), pp.269-275.

[9] Neville, A., 1995. Chloride attack of reinforced concrete: an overview. Materials and Structures, 28(2), p.63.

[10] Papadopoulos, M.P., Apostolopoulos, C.A., Zervaki, A.D. and Haidemenopoulos, G.N., 2011. Corrosion of exposed rebars, associated mechanical degradation and correlation with accelerated corrosion tests. Construction and Building Materials, 25(8), pp.3367-3374.

[11] ASTM Standard G1. Standard practice for preparing, cleaning, and evaluating corrosion test specimens, ASTM International, West Conshohocken, PA; 2011.

[12] Allam, I.M., Maslehuddin, M., Saricimen, H. and Al-Mana, A.I., 1994. Influence of corrosion on the mechanical properties of reinforcing steel. Construction and atmospheric Building Materials, 8(1), pp.35-41.

[13] Apostolopoulos, C. and Papadakis, V.G., 2004. Mechanical behavior of concrete steel bars of monumental structures. In Proceedings of the second Panhellenic conference on appropriate interventions for the safeguarding of monuments historical buildings, Thessaloniki, Greece (p. 14).

[14] ASTM B117 – 11, 2011, “Standard Practice for Operating Salt Spray (Fog) Apparatus”,

[15] Alcántara, J., Chico, B., Díaz, I., De la Fuente, D. and Morcillo, M., 2015. Airborne chloride deposit and its effect on marine atmospheric corrosion of mild steel. Corrosion Science, 97, pp.74-88.

[16] Pongsaksawad, W., Viyanit, E., Sorachot, S. and Shinohara, T., 2017. Corrosion assessment of carbon steel in Thailand by atmospheric corrosion monitoring (ACM) sensors. Journal of Metals, Materials and minerals, 20(2).

[17] Melchers, R.E., 2014. Long-term immersion corrosion of steels in seawaters with elevated nutrient concentration. Corrosion Science, 81, pp.110-116.

[18] Bhandari, J., Khan, F., Abbassi, R., Garaniya, V. and Ojeda, R., 2015. Modelling of pitting corrosion in marine and offshore steel structures—A technical review. Journal of Loss Prevention in the Process Industries, 37, pp.39-62.

[19] Pantelakis, S.G., Daglaras, P.G. and Apostolopoulos, C.A., 2000. Tensile and energy density properties of 2024, 6013, 8090 and 2091 aircraft aluminum alloy after corrosion exposure. Theoretical and Applied Fracture Mechanics, 33(2), pp.117-134.

[20] Adedipe, O., Brennan, F. and Kolios, A., 2016. Review of corrosion fatigue in offshore structures: Present status and challenges in the offshore wind sector. Renewable and Sustainable Energy Reviews, 61, pp.141-154.

[21] Ocaña, I.D., Linares, M.M. and de la Fuente García, D., 2012. Corrosión atmosférica de aceros patinables de nueva generación (Doctoral dissertation, Tesis Doctoral, Madrid 2012, 154).

[22] Singh, D.D.N., Yadav, S. and Saha, J.K., 2008. Role of climatic conditions on corrosion characteristics of structural steels. Corrosion Science, 50(1), pp.93-110.

[23] Urban, V., Krivy, V. and Kreislova, K., 2015. The development of corrosion processes on weathering steel bridges. Procedia Engineering, 114, pp.546-554.

[24] Tewary, N.K., Kundu, A., Nandi, R., Saha, J.K. and Ghosh, S.K., 2016. Microstructural characterisation and corrosion performance of old railway girder bridge steel and modern weathering structural steel. Corrosion Science, 113, pp.57-63.

[25] Alcántara, J., Fuente, D.D.L., Chico, B., Simancas, J., Díaz, I. and Morcillo, M., 2017. Marine Atmospheric Corrosion of Carbon Steel: A Review. Materials, 10(4), p.406.

[26] Li, H., Yu, H., Zhou, T., Yin, B., Yin, S. and Zhang, Y., 2015. Effect of tin on the corrosion behavior of seawater corrosion-resisting steel. Materials & Design, 84, pp.1-9.

[27] Kabir, M.H., Fawzia, S., Chan, T.H. and Badawi, M., 2016. Durability of CFRP strengthened steel circular hollow section member exposed to sea water. Construction and Building Materials, 118, pp.216-225.

[28] Melchers, R.E., 1999. Corrosion uncertainty modelling for steel structures. Journal of Constructional Steel Research, 52(1), pp.3-19.

[29] Sandu, A.V., Cioamaga, A., Nemtoi, G., Abdullah, M.M.A.B. and Sandu, I., 2015. Corrosion of mild steel by urban river water. Instrumentation science & technology, 43(5), pp.545-557.
[31] Gurrappa, I. and Malakondaiah, G., 2005. Corrosion characteristics of DMR-1700 steel and comparison with different steels in marine environment. Materials Science and Engineering: A, 391(1-2), pp.235-242.
[32] Qu, Q., He, Y., Wang, L., Xu, H., Li, L., Chen, Y. and Ding, Z., 2015. Corrosion behavior of cold rolled steel in artificial seawater in the presence of Bacillus subtilis C2. Corrosion Science, 91, pp.321-329.
[33] Lei, S.H.A.N., Zhang, Y.R., Wang, Y.X., Li, J.L., Jiang, X. and Chen, J.M., 2016. Corrosion and wear behaviors of PVD CrN and CrSiN coatings in seawater. Transactions of Nonferrous Metals Society of China, 26(1), pp.175-184.
[34] Jun, C.H.E.N., Zhang, Q., Li, Q.A., Fu, S.L. and Wang, J.Z., 2014. Corrosion and tribocorrosion behaviors of AISI 316 stainless steel and Ti6Al4V alloys in artificial seawater. Transactions of Nonferrous Metals Society of China, 24(4), pp.1022-1031.
[35] Tual, N., Carrere, N., Davies, P., Bonnemains, T. and Lolife, E., 2015. Characterization of sea water ageing effects on mechanical properties of carbon/epoxy composites for tidal turbine blades. Composites Part A: Applied Science and Manufacturing, 78, pp.380-389.
[36] Wang, Z., Liu, J., Wu, L., Han, R. and Sun, Y., 2013. Study of the corrosion behavior of weathering steels in atmospheric environments. Corrosion Science, 67, pp.1-10.
[37] Daopiset, S., Wanaosod, P., Hang, T.T.X. and Truc, T.A., 2008. Atmospheric corrosion of stainless steels 304 and 316 with different surface finishes. In Proceeding of the 5th Thailand Materials Science and Technology Conference (pp. 16-19).
[38] Bhamornsut, C., Chotimongkol, L., Nakkundot, R., Suphonlai, S., Jecnkhajohn, P., Kodama, & Tanabe, H. (2003). Atmospheric degradation of organic coatings in Thailand. In: Proceeding of Japan Society of Corrosion Engineers Conference.
[39] Chen, Y.Y., Tzeng, H.J., Wei, L.I., Wang, L.H., Oung, J.C. and Shih, H.C., 2005. Corrosion resistance and mechanical properties of low-alloy steels under atmospheric conditions. Corrosion Science, 47(4), pp.1001-1021.
[40] De la Fuente, D., Castano, J.G. and Morcillo, M., 2007. Long-term atmospheric corrosion of zinc. Corrosion Science, 49(3), pp.1420-1436.
[41] Han, W., Yu, G., Wang, Z. and Wang, J., 2007. Characterisation of initial atmospheric corrosion carbon steels by field exposure and laboratory simulation. Corrosion Science, 49(7), pp.2920-2935.
[42] Katayama, H., Noda, K., Masuda, H., Nagasawa, M., Itagaki, M. and Watanabe, K., 2005. Corrosion simulation of carbon steels in atmospheric environment. Corrosion science, 47(10), pp.2599-2606.
[43] Pongsaksawad, W., Viyant, E., Sorachat, S. and Shinohara, T., 2017. Corrosion assessment of carbon steel in Thailand by atmospheric corrosion monitoring (ACM) sensors. Journal of metals, Materials and minerals, 20(2).
[44] Melchers, R.E. and Jeffrey, R., 2008. The critical involvement of anaerobic bacterial activity in modelling the corrosion behaviour of mild steel in marine environments. Electrochimica Acta, 54(1), pp.80-85.
[45] C.R. Southwell, J.D. Bultman, C.W. Hummer, Estimating service life of steel in seawater, in: M. Schumacher (Ed.), 1979, Seawater Corrosion Handbook, Park Ridge, NJ: Noyes Data Corp, 374–387.
[46] Li, H., Brown, B. and Nešić, S., 2011. Predicting localized CO2 corrosion in carbon steel pipelines. CORROSION 2011.
[47] Adhithiya, P.S., 2009. A Effect of pitting corrosion on ultimate strength and buckling strength of plates--A review. Digest Journal of Nanomaterials and Biоструктуры, 4, pp.783-788.
[48] Melchers, R.E., 2004. Pitting corrosion of mild steel in marine immersion environment—Part 2: Variability of maximum pit depth. Corrosion, 60(10), pp.937-944.
[49] Stewart, M.G., 2009. Mechanical behaviour of pitting corrosion of flexural and shear reinforcement and its effect on structural reliability of corroding RC beams. Structural safety, 31(1), pp.19-30.
[50] Abdel-Ghany, R., Saad-Eldeen, S. and Leheta, H., 2008, January. The effect of pitting corrosion on the strength capacity of steel offshore structures. In ASME 2008 27th International Conference on Offshore Mechanics and Arctic Engineering (pp. 801-805). American Society of Mechanical Engineers.
[51] Roberge, P.R., 2008. Corrosion Engineering (p. 708). New York, NY, USA:: McGraw-Hill.
[52] Melchers, R.E., 1994. Pitting Corrosion in Marine Environments: A Review. Department of Civil Engineering and Surveying, University of Newcastle.
[53] Soares, C.G., Garbatov, Y., Zayed, A. and Wang, G., 2009. Influence of environmental factors on corrosion of ship structures in marine atmosphere. Corrosion Science, 51(9), pp.2014-2026.
[54] Schiroky, G., Dam, A., Okeremi, A. and Speed, C., 2013. Pitting and crevice corrosion of offshore stainless steel tubing: Safe construction demands proper materials. Offshore, 73(5).
[55] Pistorius, P.C. and Burstein, G.T., 1992. Metastable pitting corrosion of stainless steel and the transition to stability. *Phil. Trans. R. Soc. Lond. A*, 341(1662), pp.531-559.
[56] Melchers, R.E., 2005. Effect of immersion depth on marine corrosion of mild steel. *Corrosion*, 61(9), pp.895-906.
[57] Melchers, R.E., 2002. Effect of temperature on the marine immersion corrosion of carbon steels. *Corrosion*, 58(9), pp.768-782.
[58] Younis, A.A., El-Sabbah, M.M.B. and Holze, R., 2012. The effect of chloride concentration and pH on pitting corrosion of AA7075 aluminum alloy coated with phenyltrimethoxysilane. *Journal of Solid State Electrochemistry*, 16(3), pp.1033-1040.
[59] Mercier, A.D. and Lumbard, E.A., 1995. Corrosion of mild steel in water. *British Corrosion Journal*, 30(1), pp.43-55.
[60] Al-Fozan, S.A. and Malik, A.U., 2008. Effect of seawater level on corrosion behavior of different alloys. *Desalination*, 228(1-3), pp.61-67.
[61] Al-Fozan, S.A. and Malik, A.U., 2008. Effect of seawater level on corrosion behavior of different alloys. *Desalination*, 228(1-3), pp.61-67.
[62] Forsyth, D.S., 2011. Non-destructive testing for corrosion. *Corrosion Fatigue and Environmentally Assisted Cracking in Aging Military Vehicles* (RTO-AG-AVT-140).
[63] Scott PM, Thorpe TW, Silvester R 1983Rate-determining process for corrosion fatigue crack growth in ferrite steels in sea water. *CorrosSci*; 23(6):559–75.
[64] AdedipeO, BrennanF, KoliosA. 2015. Corrosion fatigue crack growth in offshore wind monopile steel HAZ material. In:Proceedings of the 5thinternational conference on marine structures analysis and design of marine structures V. Taylor and Francis Group; p.207–212.
[65] Schraumann P, Lochte-Holtgreven S, Steppeler S. 2011. Special fatigue aspects in support structures of offshore wind turbines. Mater Sci Eng Technol; 42 (12):1075–81.
[66] Healy, J. and Biliingham, J., 1997. *A review of the corrosion fatigue behaviour of structural steels in the strength range 350-900MPa and associated high strength weldments*. HSE Books.
[67] Shiller, D.A. and Aylor, D.M., 2005, January. Factors Affecting Corrosion Performance and Testing of Materials and Components in Sea Water. In *Corrosion 2005*. NACE International.
[68] WILHELM, E., 1967. *TOMASHOV, ND-THEORY OF CORROSION AND PROTECTION OF METALS*.
[69] Graedel, T.E.; Mc Gill, R. Degradation of materials in the atmosphere. 1986, *Environ. Sci. Technol.*, 20, 1093–1100.
[70] ISO, B., 2012. 9223, Corrosion of metals and alloys—Corrosivity of atmospheres—Classification, determination and estimation. The British Standard Institute.
[71] Alcântara, J., Fuente, D.D.L., Chico, B., Simancas, J., Díaz, I. and Morcillo, M., 2017. Marine Atmospheric Corrosion of Carbon Steel: A Review. *Materials*, 10(4), p.406.
[72] Kimura, M., Mizoguchi, T., Kihira, H. and Kaneko, M., 2006. Various scale analyses to create functioning corrosion products. In *Characterization of Corrosion Products on Steel Surfaces* (pp. 245-272). Springer, Berlin, Heidelberg.
[73] Ming, L.I.U., CHENG, X., Xiaogang, L.I., Guanhua, L.I.U., Jingyu, P.A.N.G. and Yanchen, Z.H.U., 2016. Corrosion Behavior of Cr Modified HRB400 Steel Rebar in 2% NaCl Solution. *Corrosion Science and Protection Technology*, 27(6), pp.559-564.
[74] Della Rovere, C.A., Aquino, J.M., Ribeiro, C.R., Silva, R., Alcântara, N.G. and Kuri, S.E., 2015. Corrosion behavior of radial friction welded supermartensitic stainless steel pipes. *Materials & Design (1980-2015)*, 65, pp.318-327.
[80] Reis, D.A., Couto, A.A., Domingues Jr, N.I., Hirschmann, A.C., Zepka, S. and de Moura Neto, C., 2012. Effect of artificial aging on the mechanical properties of an aerospace aluminum alloy 2024. In Defect and Diffusion Forum (Vol. 326, pp. 193-198). Trans Tech Publications.

[81] Wang, S.S., Huang, I.W., Yang, L., Jiang, J.T., Chen, J.F., Dai, S.L., Seidman, D.N., Frankel, G.S. and Zhen, L., 2015. Effect of Cu content and aging conditions on pitting corrosion damage of 7xxx series aluminum alloys. Journal of The Electrochemical Society, 162(4), pp.C150-C160.

[82] NECȘULESCU, D.A., 2011. The effects of corrosion on the mechanical properties of aluminum alloy 7075-T6. UPB Sci. Bull, 73, pp.223-229.

[83] Iliyasu et al, 2014, “The Susceptibility of Austenitic Stainless Steel to Stress Corrosion Cracking in Sodium Chloride” American Journal of Engineering Research (AJER)e-ISSN : 2320-0847, ISSN : 2320-0936 Volume-03, Issue-01, pp-180-184

[84] Gamboni, O.C., Moreto, J.A., Bonazzi, L.H.C., Ruchert, C.O.F.T. and Bose Filho, W.W., 2014. Effect of salt-water fog on fatigue crack nucleation of Al and Al-Li alloys. Materials Research, 17(1), pp.250-254.

[85] Elsarii, S.M., 2013. Behaviour of stress corrosion cracking of austenitic stainless steels in sodium chloride solutions. Procedia Engineering, 53, pp.650-654.

[86] Congleton, J. and Wilks, T.P., 1988. The air fatigue and corrosion fatigue of a 13% Cr turbine blade steel. Fatigue & Fracture of Engineering Materials & Structures, 11(2), pp.139-148.

[87] Scatigno, G.G., Ryan, M.P., Giuliani, F. and Wenman, M.R., 2016. The effect of prior cold work on the chloride stress corrosion cracking of 304L austenitic stainless steel under atmospheric conditions. Materials Science and Engineering: A, 668, pp.20-29.

[88] Zupanc, U. and Grum, J., 2010. Effect of pitting corrosion on fatigue performance of shot-peened aluminum 7075-T651. Journal of Materials Processing Technology, 210(9), pp.1197-1202.

[89] Zhong, X., Bali, S.C. and Shoji, T., 2017. Accelerated test for evaluation of intergranular stress corrosion cracking initiation characteristics of non-sensitized 316 austenitic stainless steel in simulated pressure water reactor environment. Corrosion Science, 115, pp.106-117.

[90] Scott, P.M., 2007. An overview of materials degradation by stress corrosion in PWRs. European Federation of Corrosion Publications, 51, p.3.

[91] Carter, C.S., 1971. Stress corrosion crack branching in high-strength steels. Engineering Fracture Mechanics, 3(1), pp.1-13.

[92] Contreras, A., Albiter, A., Salazar, M. and Perez, R., 2005. Slow strain rate corrosion and fracture characteristics of X-52 and X-70 pipeline steels. Materials Science and Engineering: A, 407(1-2), pp.45-52.

[93] N Eliaz et al., 2002, Characteristics of Hydrogen Embrittlement, Stress Corrosion Cracking and Tempered Martensite Embrittlement of High Strength Steels, Engineering Failure Analysis, 9, 167-184.

[94] Fernandez, J., 2016. Retraction Statement: Stress corrosion cracking of high strength stainless steels for use as strand in prestressed marine environment concrete construction. Materials and Corrosion, 67(8), pp.888-888.

[95] Iannuzzi, M., Barnoush, A. and Johnsen, R., 2017. Materials and corrosion trends in offshore and subsea oil and gas production. npj Materials Degradation, 1(1), p.2.

[96] Dong, X.Q., Li, M.R., Huang, Y.L., Feng, L.J. and Cui, X., 2015. Effect of Potential on Stress Corrosion Cracking of 321 Stainless Steel under Marine Environment. In Advanced Materials Research (Vol. 1090, pp. 75-78). Trans Tech Publications.

[97] Wan, H., Liu, Z., Du, C., Song, D. and Li, X., 2015. Stress corrosion behavior of X65 steel welded joint in marine environment. International Journal of Electrochemical Science, 10, pp.8437-8446.

[98] Fernandez, J., 2015. Retracted: Stress corrosion cracking of high strength stainless steels for use as strand in prestressed marine environment concrete construction. Materials and Corrosion, 66(11), pp.1269-1278.

[99] Xie, Y. and Zhang, J., 2015. Chloride-induced stress corrosion cracking of used nuclear fuel welded stainless steel canisters: A review. Journal of Nuclear Materials, 466, pp.85-93.

[100] Hsu, C.H., Chen, T.C., Huang, R.T. and Tsay, L.W., 2017. Stress Corrosion Cracking Susceptibility of 304L Substrate and 308L Weld Metal Exposed to a Salt Spray. Materials, 10(2), p.187.

[101] Nikolaos D et al., 2016, Effect of corrosion induced hydrogen embrittlement and its degradation impact on Tensile properties and fracture toughness of Al-Cu-Mg 2024 Alloy, 21st European Conference on Fracture, Structural Integrity Procedia02, 573-580.

[102] Ma, H.C., Liu, Z.Y., Du, C.W., Wang, H.R., Li, X.G., Zhang, D.W. and Cui, Z.Y., 2015. Stress corrosion cracking of E690 steel as a welded joint in a simulated marine atmosphere containing sulphur dioxide. Corrosion Science, 100, pp.627-641.
[103] Zvirko, O.I., Savula, S.F., Tsependa, V.M., Gabetta, G. and Nykyforchyn, H.M., 2016. Stress corrosion cracking of gas pipeline steels of different strength. Procedia Structural Integrity, 2, pp.509-516.