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The prevention of corrosion and corrosion stress cracking on structural members of fixed deep sea oil rigs

Liam Denham, Zulfiqar Khan
Bournemouth University
School of Design, Engineering & Computing
Talbot Campus, Fern Barrow
Poole, BH12 5BB, UK
I7997884@bournemouth.ac.uk

Abstract

The effect of corrosion and corrosion stress cracking on deep sea oil rigs are costing the oil industry millions of pounds a year. Failures caused by corrosion have been a problem for hundreds of years and constantly put lives at risk. The solution presented in this paper aims to reduce the effects of corrosion on the structural members of a deep sea oil rig; firstly by reducing the corrosion rate and secondly by reducing the effects of corrosion stress cracking. This paper shows how I have achieved this through changing the composition and manufacturing process of S355 steel.

Keywords: Corrosion, Corrosion Prevention, Corrosion Stress Cracking, Corrosion in the Oil Industry.

1. Introduction

The effect that corrosion is having on deep sea oil rigs is costing the industry billions of pounds 'Kermani, Harr [1]'. The location of the oil that needs to be extracted has meant that offshore structures are required in environments with very harsh operation conditions. This has led to these structures being subject to conditions that are causing corrosion to occur on the structural members. Rigs that have failed due to corrosion include; Placid L10a in 1983 and the Mariners Energy oil rig in 2010 'Baram [2]'.

The specific type of steel used in the structural members of a number of oil rigs will be considered. This is steel grade S355 which conforms to the standards BS 7191. Properties of S355 can be seen insection 5.

Corrosion types that have been identified to occur on the structural members of deep sea oil rigs are surface corrosion and pitting corrosion 'Bull [3]'. Since the presence of pitting corrosion can lead to corrosion stress cracking, the prevention of pitting corrosion is highly important in reducing failures in structural members. It is important to carry out a critique of already existing methods of corrosion prevention for marine structures in order to compare against the solutions I will be proposing.

In this paper an analysis of the relationship between material composition and corrosiveness will be undertaken, including how increasing or reducing certain elements of a material can reduce the effects of corrosion occurring.A study on how corrosion can lead to corrosion stress cracking will also be an important factor in determining a solution to the given problem. An investigation into how using a certain manufacturing process will help reduce the effects of corrosion stress cracking in the structural members of an oil rig.

2. State of the Art in Corrosion Prevention for Deep Sea Oil Rigs

A method for tackling the problem of the corrosion for structural members of a deep sea oil rigs has been given by David W. Crawford by which a polyamine and epoxy jacket is placed around either the virgin steel part of installed after the rig has been erected'Crawford [4]'. Jean P. Maes has also contributed a sacrificial cathode protection system which uses a sacrificial anode which will corrode instead of the rig due to the difference in potential between the rig and the anode 'Maes[5]'. Other technologies such as Paint coatings, Zinc silicate primers and Nano structured Platinum coatings are used to reduce the effects of corrosion on marine structures 'Balbyshev, et al [6]'.

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3. Underlying Theory

The process of corrosion takes place through the action of electrochemical cells. Corrosion is caused by the loss of electrons from the anode to the cathode. This causes oxidation of metallic atoms. In order for this reaction to occur an electrolyte is needed, in this case the electrolyte is sea water 'Jones [7]'.

Corrosion stress cracking can occur when a material under tensile stress is subjected to a corrosive environment. At a specific point of stress concentration, it is more likely for these cracks to grow and ultimately result in a failure.

4. Problem Identification

The problem that has been identified is the difficulty in preventing corrosion on structural members of deep sea oil rigs. This is a significant problem because when corrosion reaches certain propagation it can weaken the structural integrity of the members which leads to corrosion stress cracking and eventually failure. Failure on such a structure can not only cost the industry millions of pounds but also put lives at risk 'Kermani, Harr [1]'. Corrosion stress cracking occurs when there is the combined effect of tensile stress and a corrosive environment'NACE [8]'. Pitting corrosion can be highly responsible for said cracks as pits create a stress concentration point at which cracks are more likely to form, these cracks can then propagate at various rates between 10^{-3} to 10mm/h 'NACE [8]'. Corrosion stress cracking can occur when little visible corrosion has taken place. This is due to hydrogen embrittlement. Hydrogen tends to be attracted to regions of high tri-axial tensile stress where the metal structure is dilated. Thus, it is drawn to the regions ahead of cracks or notches that are under stress. The dissolved hydrogen then assists in the fracture of the metal. These effects lead to cracking of the material, cracks may be either inter- or trans-granular. Crack growth rates are typically relatively rapid, up to 1mm/s in some of the most extreme cases 'National Physics Laboratory [9]'.

The cause of the difficulty for corrosion resistance solutions is the harsh environment in which the oil rigs have to operate. The corrosive nature of the environment is largely down to the chloride content in the sea water which makes it a very efficient electrolyte and therefore very corrosive to unprotected steel alloys. Due to the structure being in a highly stressed state it is also very susceptible to hydrogen induced cracking due to selective

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stress corrosion 'Newman [10]'. The problem is further complicated by the action of the waves. This creates dynamic loading on the structure which can further increased the rate of crack propagation. The abrasive nature of the sea also makes coating the steel limited in its success as the dynamic and abrasive nature of the environment quickly erode the coatings leaving the steel substrate exposed and unprotected.

Corrosion rates can differ dependant on where the structural member is in relation to the sea level. The most extreme rates of corrosion occur in the 'splash zone' (Figure 1) 'Peter [11]'. In this zone, steel projecting out of the ocean is subject to continuous wetting with oxygen-rich sea water and protective oxide films are periodically, removed by impingement. The attack rate is far higher than that of the submerged zone or the atmospheric zone 'Creamer [12]'.

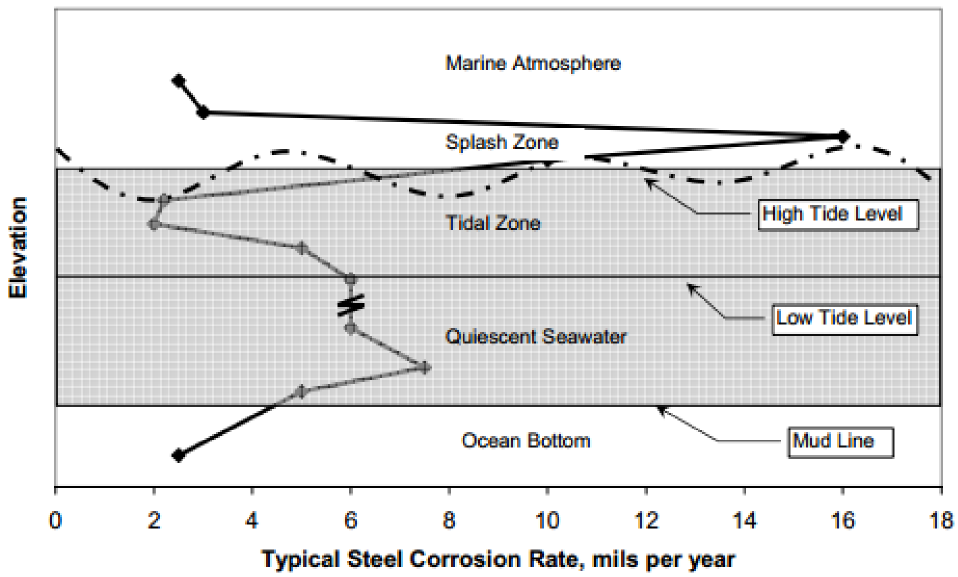

Figure 1: Corrosion rate relative to sea level 'Creamer [12]'

The solution presented by David W. Crawford'Crawford [4]' provides good protection against the corrosive nature of the environment. However this design is specific to circular cross section beams and not all structural members on an oil rig are uniform to this type of cross section. It has also stated by Crawford that this solution will only increase life expectancy of the structure by approximately 5 years, this time scale is not seen to be sufficient to warrant the cost of the solution.

Although highly suitable for many marine applications, the sacrificial cathode protection system 'Maes[5]'is limited when relating to oil rig corrosion prevention. The Alloys used for the anodes on such a system can be very expensive so for a structure such as oil rigs would incur a large cost. These anodes corrode at a highly accelerated rate and therefor need to be replaced often to maintain functionality. The current capacity for anodes can be limited by their size meaning performance for corrosion resistance can be limited. Dissolution of the anodes can also lead to contamination of the environment 'Baraud, et al[13]'.There is also a restriction when using the sacrificial anodes to protect the splash zone, this is because sacrificial anodes work best when the metal they are protecting is completely submerged in the same electrolyte, however in the splash zone this is not the case so protection here is limited.

Coatings that are adhered directly to the surface of the steel do not provide a lasting protective layer. This is because the Abrasive nature of the environment erodes these coatings exposing the bare steel below. Nanostructured platinum coatings do provide a longer lasting protective layer than most but it is not indefinite and comes at a very high cost 'balbyshev, et al [6]'.

A non-destructive material characterisation and material loss evaluation in large historic military vehicles was conducted 'Saeed, et al [14]'. The aim of this experiment was to measure and analyse the corrosion rate effectively through non-destructive methods. The method used to conduct the analysis was X-ray Fluorescent (XRF) and ultrasonic scanning. Experimental results for XRF were obtained for an M10 and Centaur-A27L tank. The conclusions of this study show the difference in maximum and minimum material loss. This material loss was due to the presence of corrosion. The difference in material loss between the maximum and minimum points has been identified at 4.30mm for the M10 tank and 7.50mm for the Centaur-A27L. The quality of results for the M10 can be taken has highly reliable. This is because a match quality of 9.70 - 9.80 is achieved. However the match quality of 5.20 - 6.60 for the Centaur-A27L is relatively low in comparison and therefor the reliability of these results can be questioned. This paper also gives useful information on corrosion rates for different environments of various metal types; this includes the corrosion rate of 26-104μm/y for Fe in a marine environment. Fe is a substantial constituent in S355 steel, proving the importance for the inclusion of corrosion protection.

Recent research 'Saeed, et al [15]' shows the importance of corrosion control in an uncontrolled environment, which is useful knowledge in terms of an oil rig. The research provides an understanding of the failure mechanisms because of corrosion and linkages to the materials' characteristics. A study on the environmental effects has also been conducted to relate corrosion activity within context. It has been identified that it is not always possible to control the environment and therefor methodologies have been devised to slow down the process of structural degradation.

The solution that will be investigated in this paper is to change the composition of the steel at the manufacturing stage in order to reduce the occurrence of corrosion. The paper will look into how changing certain percentages of Silicon (Si) and Nickel (Ni) can help prevent ferric oxide forming. An investigation will also be carried out into how manufacturing processes can reduce the effect of stress corrosion cracking on the structural members of the oil rig.

5. Discussion and Results of the Solution

The proposed solution is to increase the corrosion resistance of the material by changing the chemical composition. Two studies have been carried out in investigating the effects on corrosion resistance firstly by adding more silicon to the compound and then adding more nickel. The base material will be Steel S355 which has a chemical composition of; 0.2% C, 0.5% Si, 1.6% Mn, 0.035% P, 0.035% S, Fe balance 'Steel Grades[16]'. The corrosion rate of this material within the splash zone is 16mils per year 'Peter [11]', converted into Si units is 0.4mm per year.

Each 0.1% increase in silicon content will result in a 6% decrease in corrosion rate'kirk [17]'. This data will be used to extrapolate data for the effect on corrosion behaviour for increasing Silicon content. Table 1 shows a table of corrosion rate decrease for differing silicon content.

Si % Content	Corrosion Rate mm/year
0.5	0.4
0.6	0.376
0.7	0.353
0.8	0.332
0.9	0.312
1	0.293
1.1	0.276
1.2	0.259
1.3	0.244
1.4	0.229
1.5	0.215
1.6	0.203
1.7	0.19
1.8	0.179
1.9	0.168
2	0.158

Table 1: Corrosion rates for differentiated silicon content

Table 1 shows the predicted corrosion rates of S355 steel with modified silicon content. This data has been put into a graph (figure 2) to clearly demonstrate the correlation.

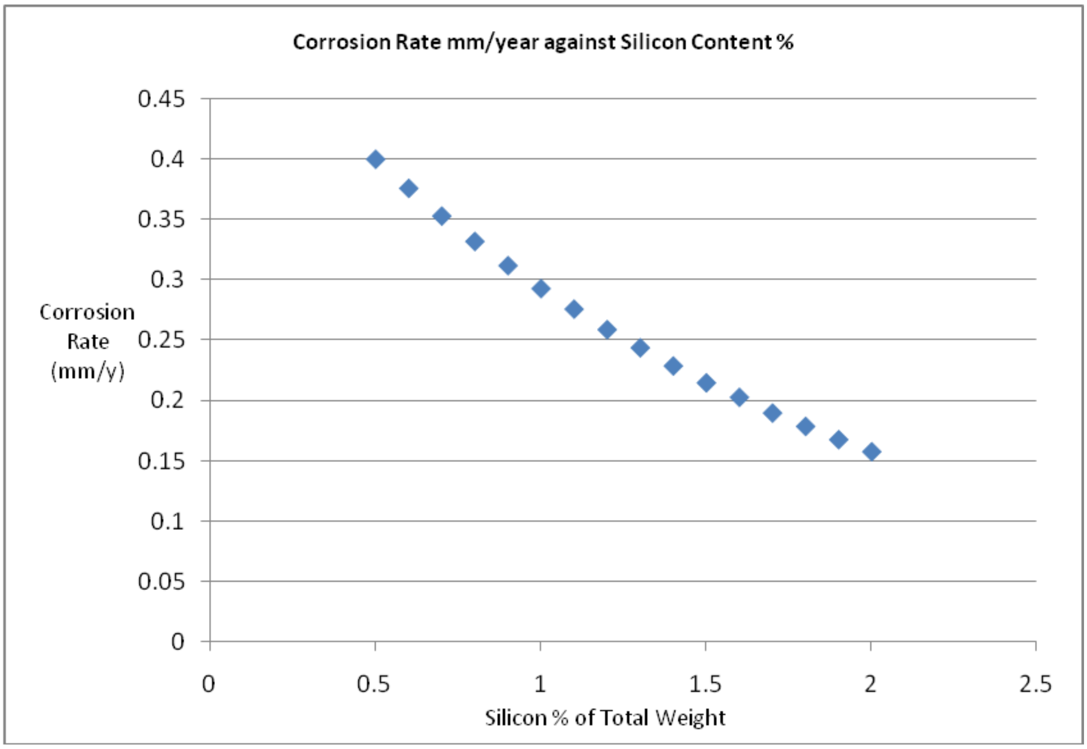

Figure 2: Graph showing corrosion rate/silicon content

From the graph it can be seen that there is a clear relation between the silicon content in the steel and the corrosive resistant properties it inherits. By increasing the silicon content in the material at the manufacture stage can increase its resistance to corrosion. The corrosion rate has reduced to less than 50% in 2% Silicon steel compared to 0.5%. The corrosion rate acts on all surfaces of the structural members on an oil rig, therefor if the member is a box section beam then the corrosion will act on 4 surfaces meaning after one year the cumulative corrosion propagation will be 1.6mm. By using 2% Si content steel will reduce this to approximately 0.6mm. This graph could be extrapolated to predict the properties of steel with Si contents greater than 2%. However this will begin to induce unfavourable characteristic in the material. By adding too much Silicon to the steel can lead to difficulties in welding and can make the material brittle which is unsuitable when under the large tensile stresses that occur in an oil rig. Adding silicon to steel reduces thecorrosion rate via passivation. Adding silicon makes the metal more passive and hence it becomes less affected by the environment, in this case sea water.

Corrosion rates have also been calculated for the addition of Nickel to the material composition. Each 0.1% increase in Nickel content will result in a 7% decrease in corrosion

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rate 'Kirk [17]'.This data will be used to extrapolate data for the effect on corrosion behaviour for increasing Nickel content. Table 2 shows a table of corrosion rate decreased for differing Nickel content.

Ni % Content	Corrosion Rate mm/year
0.5	0.4
0.8	0.322
1.1	0.259
1.4	0.208
1.7	0.167
2	0.135
2.3	0.108
2.6	0.087
2.9	0.07
3.2	0.056
3.5	0.045
3.8	0.036
4.1	0.029
4.4	0.024
4.7	0.019
5	0.015

Table 2: Corrosion rate for differentiated nickel content

Table 2 shows the predicted corrosion rates of S355 steel with modified Nickel content. This data has been put into a graph (figure 3) to clearly demonstrate the correlation.

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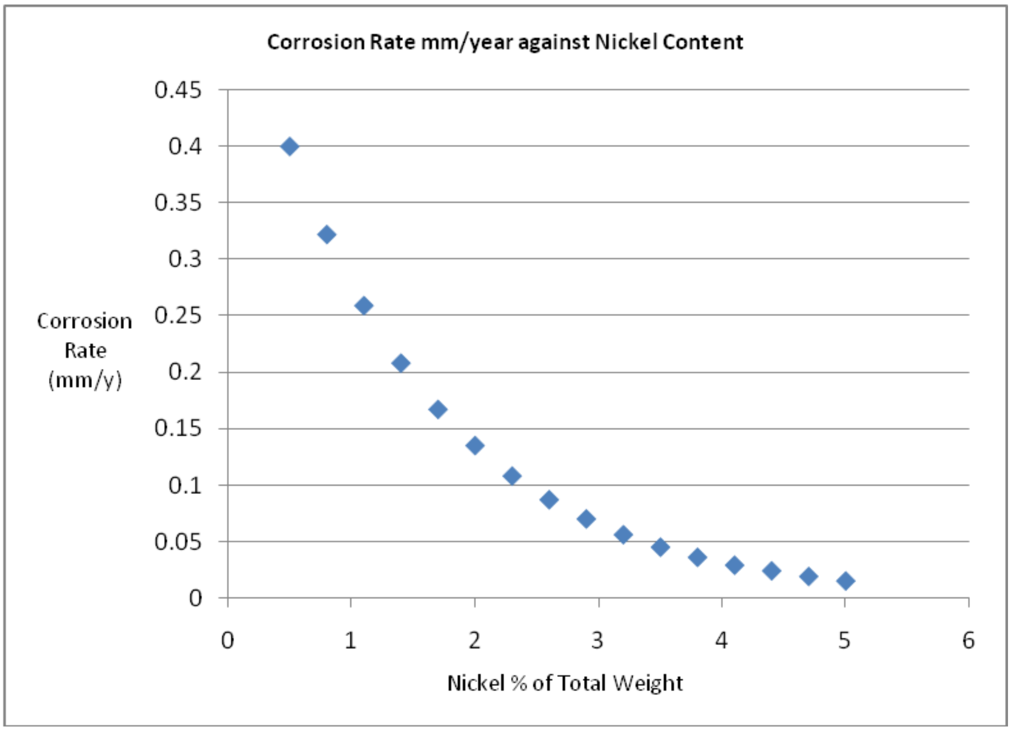

Figure 3: Graph showing corrosion rate/nickel content %

From the graph the correlation between Nickel content and corrosion rate can be seen. The corrosion rate is decreased with the addition of Nickel to the metal compound. Up to 5% Nickel can be added with little unfavourable effects on the other characteristics of the metal, unlike silicon which would only allow up to approximately 2% without inducing brittle characteristics into the metal. It can be seen that the line begins to flatten out at around 3% Nickel addition, after this stage the addition of more nickel is having a lessened effect on the corrosive properties. However when Nickel content reaches 5% it can provide more beneficial properties to the material. These include improved machinability and ductility as well as a high resistance to fatigue. These properties are favourable to the application of structural members of oil rigs as it will give the members good resistance to the dynamic loading create by the waves.

Nickel does however incur a relatively high cost of £2.22 per kg 'Investment mine [18]', in comparison to Silicon at £0.40 per kg 'Investment mine [19]'. Therefor adding extra Nickel past 3% (the point at which the line flattens out on the graph) would not merit the cost of the addition.

The other problem identified with the structural members of deep sea oil rigs is there nature to be susceptible to corrosion stress cracking. In order to decrease the effects of corrosion stress cracking, stress relief annealing should be used. This will involve heating the material to its critical temperature approximately 800-850°C and allowing to cool. By applying this process to the manufacture of the structural members will relieve the residual stresses that are present in the steel. This will reduce the chance of cracks occurring. For a structure as large as oil rigs full stress relief can be difficult to obtain. Therefor stress relief around specific stress concentration points such as joins and welds should be applied. Areas such as the splash zone should also be considered as a high priority.

6. Conclusions

The harsh environment for which an oil rig operates in makes it very difficult to design against corrosion. Due to the dynamic and erosive nature of the waves and sea debris conventional coatings of the steel are unsuitable. However, changing the composition of the material can help reduce the corrosivity of that material. By increasing the silicon content of S355 steel up to 2% will drop the corrosion rate from 0.4mm per year to 0.158mm per year. The increase of silicon should not exceed 2% as this will cause the material to inherit undesirable characteristics such as brittleness. It can also be seen that introducing Nickel into the material composition of S355 steel can also reduce the corrosion rate to a slightly greater extent than silicon. The percentage of Nickel that should be added is 3%. It can be concluded that the addition of Nickel is slightly more beneficial than the addition of Silicon in relation to corrosion resistance but comes at a greater cost. Although both the methods described will reduce corrosion to an extent neither will completely eradicate the problem. Therefor stress relief annealing should be used in the manufacturing process in order to reduce the likelihood of stress corrosion cracks occurring. Further work on this matter is to investigate the relationship between Nickel and Silicon content with the UTS of the material and correlate this to corrosion resistance.

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