Citation: Qaban, A. & Naher, S. (2019). Investigation of corrosion resistance of high-strength low-alloy (HSLA) steel in fresh and salt water for pipeline application. AIP Conference Proceedings, 2146, 20021. doi: 10.1063/1.5123708

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Conference Paper *in* AIP Conference Proceedings · August 2019

DOI: 10.1063/1.5123708

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Cite as: AIP Conference Proceedings **2146**, 020021 (2019); https://doi.org/10.1063/1.5123708

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Investigation of Corrosion Resistance of High-Strength Low-Alloy (HSLA) Steel in Fresh and Salt Water for Pipeline Application

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Abstract. Corrosion behaviour of HSLA steel immersed in fresh and salt water for a four weeks period was investigated by weight loss method at room temperature. The main applications considered for the current work are underground water pipes and the pipeline systems in desalination plants. The corrosion behaviour in the saltwater medium was more severe but the rate was found to drop in the fourth week, presumably due to the formation of a protective passive film on the surface. The combination of ferrite and cementite phases in the microstructure contributed to promoting the corrosion rate due to the initiation of galvanic cells between both phases.

INTRODUCTION

Recently, high-strength low-alloy (HSLA) steel has attracted much attention by various engineering applications, such as pipelines, construction, offshore structures and automobiles [1]. The main features of HSLA steel include but are not limited to high strength, good ductility and low weight which make its use possible in most of the engineering fields.

HSLA steel is an ideal option for pipeline construction when considering mechanical properties, machinability and weldability. However, corrosion was not the primary consideration during the development of HSLA steel and hence more work is essential to understand the reactivity of the steel in a given environment. Corrosion is a natural process that causes damage and degradation of metal properties due to some chemical reactions with external environments [2].

Pipelines used to transport water are of importance and care must be taken to isolate the material of pipes from the water or any corrosive materials for public health and safety. America's underground water pipes have been reported to suffer serious deterioration due to corrosion, causing considerable social and economic disruptions [3]. The United States Environmental Protection Agency (EPA) has reported that $655 billion will be spent over the next two decades to upgrade water systems in the USA. Despite the fact that these underground water networks are utilised to transport pure water, long-term use is found to promote corrosion of the pipes and degradation of the steel properties which could raise the risk of contamination of drinking water.

In desalination plants, pipelines are utilised to transport sea water for further processing to produce water suitable for human consumption and irrigation [4]. Due to the high salinity of sea water, the internal surfaces of the pipes experience high corrosion rates under a steady flow of saltwater [5]. Consequently, the lifetime of the pipe is reduced which in turn requires high replacement and maintenance costs [6]. The deterioration is not limited to chemical

International Conference on Key Enabling Technologies (KEYTECH 2019)
AIP Conf. Proc. 2146, 020021-1–020021-5; https://doi.org/10.1063/1.5123708
Published by AIP Publishing. 978-0-7354-1891-2/$30.00

behaviour but involves a loss in strength caused by the reduction of pipe material thickness. In extreme cases, further damage can reach pumps and valves leading to structural failure [5].

In the current study, the corrosion behaviour of HSLA steel in freshwater and saltwater environments has been studied by weight loss technique at room temperature. The main fields of application to be considered for the steel in fresh and salt water are underground water pipes and the pipeline systems in desalination plants, respectively. The knowledge of reactivity of HSLA steel with such environments can help in determining the performance and longevity of life-sustaining water pipes.

EXPERIMENTAL

The examined HSLA steel was hot rolled to a plate thickness of 15mm then cooled down to room temperature at 30^{o}C min^{-1}. The detailed composition of the steel is presented in TABLE 1. Cubic samples with the dimensions 1x1x1 cm were machined from the plate.

TABLE 1. The full composition of the investigated HSLA steel, wt-%.

C	Mn	Si	S	P	Al	N	Fe
0.05	1.4	0.47	0.0043	0.005	0.02	0.009	Bal.

The surfaces of the specimen were ground and polished then rinsed with distilled water, degreased in alcohol and air dried. For examination, samples were hung with wires and immersed in the solution for a pre-determined period. In this paper, two different aqueous environments were prepared for examination; freshwater with a pH level of 7 and saltwater with a pH level of 8.1. Each specimen was kept in the solution at a weekly interval up to four weeks.

The initial mass of each sample was measured by an electronic scale and recorded. After each exposure time, the samples were taken out from the cell, washed with distilled water, dried and then reweighed to determine the mass. The obtained mass loss value given in gram is used to calculate the corrosion rate for reliable analysis based on equation (1) [7]:

$$\text{Corrosion rate (mm/year)} = \frac{W \times 8.76 \times 10^4}{T \times D \times A} \tag{1}$$

Where W is the mass loss in gram, T is the time of exposure in hour, D is the density of the material in g/cm3 and A is the area of the sample in cm^2:

RESULTS

The corrosion rates of HSLA steel in fresh and salt water at a weekly interval, calculated from the weight loss tests, are shown in Fig. 1. In freshwater, the corrosion rate was found to increase with the time of exposure for the entire period. Similar behaviour was noted at saltwater up to 3 weeks but this was followed by a drop in corrosion rate at the fourth week. There is an almost linear dependence of corrosion rate on exposure time in freshwater. However, the increase rate of corrosion rate in saltwater medium varies considerably, in which corrosion proceeds at a faster rate at the first week followed by a slower rate in the following two weeks. This was followed by a drop in the corrosion rate in the fourth week. In general, the corrosion attack in saltwater is approximately 5.5 higher than freshwater because saltwater is known to be a strong oxidising agent. The maximum corrosion rates exhibited by the steel in salt and fresh water are 1.10 and 0.4 mm year^{-1}, respectively.

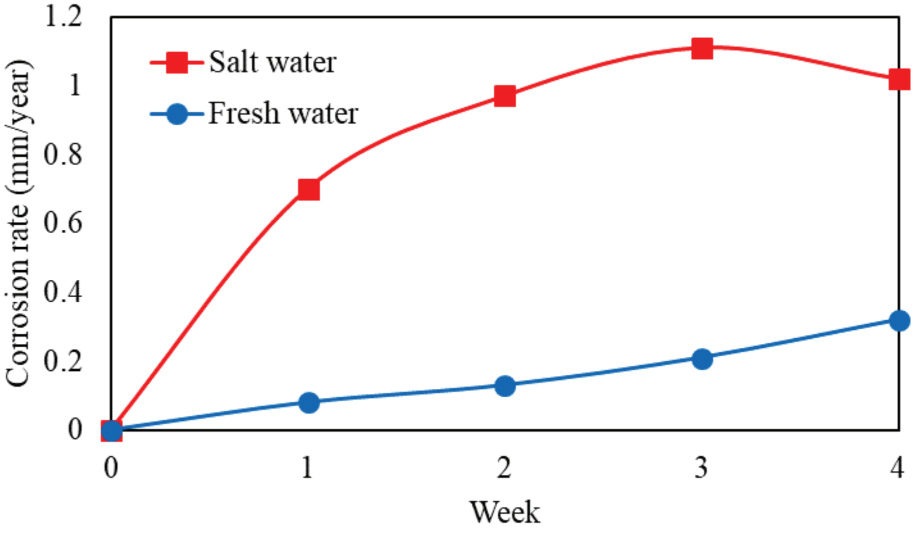

FIGURE 1. The corrosion rate of HSLA steel in salt and fresh water at a weekly interval

DISCUSSION

Corrosion Reaction

The severe corrosive attack of the aqueous salt solution on the HSLA steel is ascribed to the reaction of oxygen with the solution surface of the steel. The anodic reaction occurs as the steel losses its electrons leading to its dissolution. The cathodic reaction occurs simultaneously as the electrons are transferred to the oxygen-rich region on the surface. The cathodic reaction can be expressed by the following formula:

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^- \quad (2)$$

The anodic reaction is more complex as it involves dissolution of steel and formation of iron compounds. The whole process can be summarised as follows [8]:

$$Fe \rightarrow Fe^{2+} + 2e^- \quad (3)$$
$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \quad (4)$$
$$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3 \quad (5)$$
$$4Fe(OH)_2 + O_2 \rightarrow 2Fe_2O_3 + 4H_2O \quad (6)$$
$$Fe(OH)_3 \rightarrow FeOOH + H_2O \quad (7)$$

The amount of steel dissolution increases with the time of exposure, which can justify the increase of corrosion rate for both steels in Fig. 1. The aqueous salt solution is a strong corrosive medium when compared with freshwater. This is reflected by the high corrosion rate exhibited by the steel for the entire period. However, the deterioration rate is shown to decrease with the exposure time till the third week which indicates the occurrence of the passivation process. At this period, the iron oxide passive layer started to form but is still weak, porous and thin, thus its protection capability is limited [9]. As the corrosion process approached the fourth week, the corrosion rate dropped due to the fact that the passive film was developed and became more stable, stronger, denser, more uniform and strongly bonded to the steel's surface [10]. The corrosion species are then obstructed to reach the surface, resulting in a low corrosion rate [11].

Analysis of the microstructure

The role of the microstructure in influencing corrosion behaviour should also be considered when investigating HSLA steel. The microstructure of the current HSLA steel consists of ferrite and pearlite. Pearlite is a lamellar structure that consists of alternating layers of ferrite and cementite (Fe_3C), each of which reacts differently to corrosive environments. Ferrite has less electrochemical stability than cementite, thus inducing galvanic cells between both phases that accelerate the corrosion reaction, in which ferrite represents the anodic reaction and cementite represents the cathodic reaction [12].

Care must be taken when processing HSLA steels to control the microstructure and hence optimising corrosion properties. Ferritic steels offer excellent corrosion resistance due to the uniform distribution of the ferrite phase and the absence of pearlite. In such a case, the cathode and anode areas are located near each other so eliminating any opportunity of galvanic cell formation. However, ferritic steels are not an ideal option when considering mechanical properties so they are still less popular than other steels.

Some applications require very high levels of strength, which is achieved by utilising high cooling rates. This treatment encourages the formation of lower transformation products in the microstructure which are hard in nature, such as martensite and bainite. However, these phases have the lowest corrosion resistance among all microstructures due to the presence of high density of lattice defects, which promote corrosion. In the current work, the cooling rate was kept low enough, ~30ºC min^{-1}, to prevent the formation of lower transformation products. Refinement of grain size has been found to be beneficial in promoting corrosion resistance of HSLA steel [2]. Optimising the thermal treatment and the addition of grain refining alloys can contribute considerably in refining grain size and hence improving corrosion behaviour of HSLA steel. Improvement of mechanical properties of steels is clearly achieved at the expense of corrosion behaviour and vice versa. Generally, HSLA steel is found to combine both properties at a reasonable level.

CONCLUSIONS

In the current study, the corrosion behaviour of HSLA steel in fresh and salt water using weight loss technique has been reported. In general, the aqueous salt solution was shown to accelerate the corrosion rate considerably. In a freshwater medium, the corrosion rate was shown to increase linearly as a function of exposure time for the entire testing period. The corrosion rate in the saltwater medium was also shown to increase steadily with the exposure time but this deterioration was followed by a sudden improvement of corrosion resistance. This improvement was attributed to the formation of iron oxide passive layer which acted as a barrier obstructing any further attack. The microstructure of the current HSLA steel contains a high volume fraction of pearlite which induces galvanic cells between ferrite and cementite so enhancing the corrosion reaction.

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