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Mitigating the effect of corrosion and wear in the application of high strength low alloy steels (HSLA) in the petrochemical transportation industry—a review

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Abstract
High Strength Low Alloy (HSLA) steels have gained a wide range of acceptance not only in the automobile industries but also in the field of petrochemical transportation. They exhibit high strength to low weight ratio in addition to other key properties that stimulate their use in the petrochemical industries. Despite these properties, wear and corrosion are key inhibiting factors and major limitations in the application of the materials when exposed to carbon dioxide (CO2), hydrogen sulfide (H2S), water (H2O) and chloride (Cl) environments, which are usually found in the petrochemical industries. The corrosion possesses a great risk to steel degradation which will eventually result in a failure as a result of cracking, reduction in thickness and ultimate perforation. This paper focuses on a review of various methods available to improve the properties of HSLA steels that will mitigate against corrosion and wear in the petrochemical industries. Special attention is given to the use of HSLA steels in the pipeline, highlighting its performance and how it would be optimized by introducing chromium (Cr) for corrosion resistance.

1. Introduction
High Strength Low Alloy (HSLA) steels have been a major focal point of work for most researchers due to their ranging use and applications in engineering. HSLA steels have unique features of high strength, good ductility, high tensile strength, low yield strength, continuous yielding behavior, high strength to low weight, weldability, effective cost, and highly uniform total elongation [1, 2]. The quest for a material with high strength to establish fatigue and crack resistance without reducing the formability or increasing costs has driven the development of HSLA steel. The application of HSLA, span through the automobile, structural reinforcement, rail industries, petrochemical transportation (pipeline), etc.

HSLA has been used in oil and gas industries as pipelines for decades. It was however adopted, due to a quest for material that will withstand seismic movement, with mechanical properties of high fracture toughness, efficient weldability, low-temperature pressure, high strength and resistance to corrosion and wears. Hence, HSLA steels find applications in petrochemical industries because of the unique nature of their applications. Crude oil extraction, oil wells, offshore oilfields, etc are generally corrosive environments, due to the presence of high temperature and pressure with acidic gas [3]. Generally, most of these industries are situated far from their customers or consumption points, thus, the need for a medium for safe, durable and cheap transportation arises. It is therefore imperative to use materials which could survive harsh condition at a reduced transportation cost with limited or no corrosion effects.

The most widely used steel is carbon steel due to its cost-effectiveness and satisfactory strength, yet it has become a major focus for most researchers because of its vulnerability to wear and corrosion attack in a chloride environment [4]. In the petrochemical industry, the properties of carbon steel have made it a first choice, however, its exposure to abrasion and corrosion environment could cause disintegrations of pipelines to surface layers leading to severe damages, corrosion, wear loss and fatigue failure.

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For several years, CO$_2$ and H$_2$S have been the major sources of corrosion of steel in petrochemical transportation, if not properly handle it will lead to severe damage. A change in parameters such as temperature, pH, the partial pressure of the CO$_2$ influenced the rate of corrosion in pipelines [18–20]. A major problem associated with the oil and gas industry is the corrosion of carbon steel, resulting in great economic losses, environmental pollution, and ecological crisis. This thus takes place from downhole to surface equipment through to the processing plants and is influenced by factors such as temperature, pH, the partial pressure of the CO$_2$ [21]. Among the impurities (H$_2$O, SO$_2$, NO$_2$, O$_2$, and H$_2$S) contained in CO$_2$, H$_2$O plays an important role in the corrosiveness of the material, its presence formed solubility limit in a supercritical state (SC CO$_2$). However, due to the fluctuation of temperature and pressure, while transporting and injecting CO$_2$, H$_2$O could condense on the steel and result in a localize corrosion [22]. The presence of oxygen and water with a combined effect of electrochemical reactions could also result in material corrosion [23].

The process of corrosion is an electrochemical process, whereby an electric current flows either on a macro or micro scale, produced by the reactions of anode and cathode [24]. In the oil and gas industry, pipelines are an important aspect of petrochemical transportation. Degradation of these lines presents some danger of pipeline failure, hence failed pipelines are hazardous to humans and its environment due to their flammability, explosiveness, and toxicity. Because of the area of application (oil and gas), these materials are in contact with crude oils, petroleum products, natural gas, water, soil, and the atmosphere. Hence an understanding of the physicochemical process is required to guide against corrosion challenges. Several solutions have been designed to tackle the problems posed by corrosion such as; coatings, selection of corrosion-resistant material, correct design, application of anti-corrosive chemical, cathodic protection, control of technological parameters, etc [25]. As noted by Hagarová et al [2015], to protect the surface of the interior parts of the pipe is based on the chemical composition of the gas and the use of inhibitors while that of the external requires coating and cathodic protection [24].

### 3.1. Crude corrosiveness

Crude oil is composed of several hydrocarbon liquids of dissolved gas, water, and salts. It could also contain compounds of nitrogen, sulfur, metals, and oxygen, which could be present as dissolved gas, solid and liquid, hence refer to as contaminants [25]. The primary cause of crude corrosiveness is the presence of water droplets in the aqueous solution spread throughout the hydrocarbon phase, also the presence of micro-organisms in the aqueous solution.
crude water or fuel is another cause of crude corrosiveness \[25\]. Crude corrosiveness is expressed in terms of the Total Acid Number (TAN), Total Sulfur Content (TSC), micro-organisms, salt and water content \[25\]. However, these parameters stimulate the presence of corrosion in several ways and stages of crude production.

### 3.2. Natural gas corrosiveness

The presence of compounds such as CO\(_2\), H\(_2\)S, H\(_2\)O, organic acid and mercury could cause corrosion, hence CO\(_2\) and H\(_2\)S in natural gas dissolve in water to form an acid that aids corrosion \[25\]. Sweet corrosion is the result of CO\(_2\) while sour corrosion is caused by the presence of H\(_2\)S.

### 4. Agents of corrosion

Corrosion of steel is stimulated by several agents such as CO\(_2\), H\(_2\)O, O\(_2\), etc corrosion of metal in the presence of water is a major setback in the oil and gas industry. A major agent of corrosion is CO\(_2\), dry CO\(_2\) gas is not corrosive until it’s been dissolved in an aqueous solution through which it enables electrochemical reaction, as seen in equation (1) \[26\].

\[
\text{Fe} + \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{FeCO}_3 + \text{H}_2
\]  

Likewise, is the presence of hydrogen sulfide H\(_2\)S in water, which forms a weak acid and serves as a source of hydrogen ions which makes it corrosive, as presented in equations (2) and (3) \[26\].

\[
\text{H}_2\text{S}_{(aq)} \rightarrow \text{H}^+_{(aq)} + \text{HS}^-_{(aq)} \tag{2}
\]

\[
\text{HS}^-_{(aq)} \rightarrow \text{H}^+_{(aq)} + \text{S}^2-_{(aq)} \tag{3}
\]

Another agent of corrosion is bacteria from microbiological organisms, which produce waste such as CO\(_2\), H\(_2\)S and organic acid that causes corrosion on the pipelines.

The process of corrosion entails the transference of electrons from iron atoms in the metal to hydrogen ions or oxygen in water, as described in equations (4)–(7) \[26, 28, 29\].

\[
\text{Fe} + 2\text{H}^+ \rightarrow \text{Fe}^{2+} + \text{H}_2 \tag{4}
\]

This reaction involves two separate processes; anodic and cathodic processes equations (5) and (6) respectively. At anode oxidation of the metal takes place while at the cathode there is a reduction in the proton. Hence, it can be said that soluble iron and electron are produced at the anode while the electron is consumed by acid to produce hydrogen gas at the cathode.

\[
\text{Fe} \rightarrow \text{Fe}^{2+} + 2e^+ \tag{5}
\]

\[
2\text{H}^+ + 2e^+ \rightarrow \text{H}_2 \tag{6}
\]

Equation (7) described the reduction of oxygen at the cathode, which could take place at a location other than the iron dissolution.

\[
\text{O}_2 + 4\text{H}^+ + 4e^- \rightarrow 2\text{H}_2\text{O} \tag{7}
\]

### 5. Types of corrosion associated with pipelines

The intensity and rates of corrosion are a function of the type and concentration of an assertive ingredient, flow regime, velocity, and temperature \[25\].

i. Sweet corrosion

Sweet corrosion is caused by the presence of CO\(_2\) in water and is one of the most identified problems in the petrochemical industry. Dissolving dry CO\(_2\) gas in aqueous solution promotes electrochemical reactions, between the metal and the solution \[26, 28, 29\].

ii. Sour corrosion

When hydrogen sulfide (H\(_2\)S) is dissolved in water, it leads to sour corrosion. The reaction that takes place between the H\(_2\)S and water formed a weak acid, which leads to pipeline embrittlement. The forms of sour corrosion are uniform, pitting, and stepwise cracking \[26, 28, 29\].

iii. Oxygen corrosion

Oxygen as a strong oxidizing agent that reacts with metal. Oxygen-induced corrosion is found mostly with surface equipment or downhole through the introduction of oxygen as a result of water flooding. The presence
of this oxygen enhances the effect of corrosion of the acid gas (H₂S and CO₂). The forms of corrosion associated with oxygen are mainly uniform corrosion and pitting [26, 28, 29].

iv. Galvanic corrosion
   Galvanic corrosion results from two metallic materials with different electrochemical potential coming in contact and been exposed to the electrolytic environment. Hence the less potential material tends to corrode the first [26, 28, 29].

v. Crevice corrosion
   This is a form of localized corrosion resulting from the stagnation of fluid in a particular gap. It is caused by a difference in the concentration of chemical constituents such as O₂, which creates an electrochemical concentration cell. The difference in the electrochemical potential gives rise to either crevice or pitting form of corrosion [26, 28, 29].

vi. Erosion corrosion
   Where the passive layer of a thin film is being employed to protect the steel, there is a tendency for this layer to be washed off or damaged by high turbulent flow, thereby exposing the bare metal to corrosion. This coating or passive layer serves as a stabilizer to corrosion reaction and retards its occurrence. Factors such as the morphology of the solids in the fluid, fluid density and flow rate influence the occurrence of erosion-corrosion [26, 28, 29].

vii. Microbiologically induced corrosion
   The activities of microorganisms are responsible for this type of corrosion. The waste product (CO₂, H₂S, and organic acids) from this microorganism increases the toxicity of the fluid in the pipe, thereby corroding it [26].

viii. Stress corrosion cracking
   This is localized corrosion resulting from the combined effect of tensile stress and corrosion environment. This eventually leads to crack and sudden failure of the material [26].

6. Effect of sweet corrosion in petrochemical transportation

The effect of corrosion (such as sweet, sour and oxygen corrosion) in petroleum transportation facilities cannot be neglected as it thus, affect the integrity and functionality of the system components. The influence of this corrosion could lead to plant shut down as a result of pipeline failure. Hence, its presence presents a big danger to the economic, societal, ecological system and humanity at large. Its consequences are listed below but not limited to these [26, 30–32].

i. Causes severe damage to pipelines leading to plant shutdown
ii. Releases toxic products which are harmful to ecosystem and man
iii. Reduces production rate/volume
iv. Corrosion from microbiological material causes filters and equipment plugging, contamination of products and reduces flow rate.
   v. Due to its damage, the cost is incurred for maintenance activities.
   vi. Depletion of natural resources

7. Mitigating against sweet corrosion in oil and gas industry

The problem of corrosion faced by the oil and gas industry has been a dynamic phenomenon, that requires prompt attention. Several technical options have been identified in fighting corrosion (table 2). Managing corrosion effectively will enhance asset integrity, cost reduction and optimization of the production system. While many methods have been adopted to resist corrosion, preference will be given to surface alloying as a better option.
Surface alloying of carbon steel is essential in changing the chemical composition of the steel by infusing one or
more metal elements together. This is done to enhance its properties over the steel (carbon steel). The essence of
surface alloying is to prevent corrosion, enhanced tensile strength, and hardenability of the material. Unlike the
coating and other traditional method of corrosion resistance which are mechanically bonded, the surface
alloying is a deposition and metallurgical bonding of the alloys which becomes an integral part of the new
material formed. Surface alloying could be achieve using Ultrasonic impact treatment (UIT) or Electric
discharge and Surface alloying (EDSA) [37]. The process of UIT entails the application of ultrasonic energy on
the metal object. However, UIT is a High-Frequency Mechanical Impact (HFMI) process, that generates energy
that it’s being imparted on the treated surface of the material. Using UIT, superficial factors such as improved
hardness, compressive residual stress and decreased surface roughness which are accountable for reducing the
concentration of stress in the sub-surface microstructure and surface topography can be improved [4]. The
EDSA is a thermal process that involves melting and vaporization of the workpiece electrode, as a result, surface
alloying is applied during sparking. The working principle of this process is the boosting of moving Cr anode by
a series of capacitors short circuits with the sample surface which produces an electric arc. As a resultant effect,
the generated arc melts the electrode material particles, hence the sample surface is impacted, solidifies rapidly
and form an alloy surface [38]. Wear resistance and hardening of surface area are attributed to the
microstructural and phase transformations induced by deformation during UIT, therefore, adopting UIT
combined with the EDSA by Cr on low carbon steel, will effectively enhance the resistance of the surface layer
from corrosion and wear [38, 39].

8.1. Influence of chromium (Cr) on steel
The focus of researchers has been drawn towards developing lightweight material with improved mechanical
properties and superior corrosion performance, by alloying with Cr, magnesium, molybdenum, etc (table 3)
[40]. Addition of Cr reduces the rate at which fatigue cracks propagate, hence corrosion and fatigue resistance of
the steel is improved. Cr developed protective oxide layers on the surface of the carbon steel, thereby protecting
it from corroding. There is a tendency for sweet corrosion to be formed on the steel due to the presence of carbon
dioxide and water during production and transportation of oil and gas, hence the steel is exposed to a greater risk
degradation that could end in failure of the casing and pipelines [41]. Mitigating against this required infusing
Cr into the material for better material with good resistance to wear and corrosion [19, 20].

To alter the physical and chemical properties of the steel surface in order to guide against wear and
corrosion, deposition of Cr is an essential factor [4]. Application of a little percentage of Cr could bridge the gap
between using the traditional carbon steel which is prone to corrosion or using stainless steel which is of high
cost [41, 42]. Experiments conducted by Wei et al (2017), on the corrosion behavior of Cr steel, showed that Cr
content ratio of martensite to either bainite, ferrite, or pearlite is high and thus possess greater corrosion
resistance [43]. The most threatening form of corrosion in petrochemical transportation is sweet corrosion; it is
the most common and dangerous. However, steel with 3 wt% Cr could perfectly be used in such an
environment, as it is capable of enhancing corrosion resistance by a factor of 3–10 [43].

Table 2. Corrosion resistance [24, 33–36].

| Corrosion resistance       | Characteristics                                                                 | Example                                                                 | References |
|----------------------------|--------------------------------------------------------------------------------|------------------------------------------------------------------------|------------|
| Active Corrosion Resistance| It influences reactions that precede corrosion, including the corrosive agents to avoid corrosion. It limits the rates of anodic and cathodic processes. They are cost-effective | Inhibitors, the introduction of corrosion resistance alloy              | [35, 36]   |
| Passive Corrosion Resistance| It involves mechanical isolation of the material from corrosive agents. It consists of organic coats, metal, and non-metal layers. Removal of the protective layer could lead to corrosion | Protective film, glass fibre, epoxide and rubber                       | [24, 33]   |
| Permanent Corrosion Resistance| Permanent corrosion protection provides protection at the point of use. The stresses presented by climatic, biotic and chemical factors are relatively slight in this situation. | Tin plating, Galvanization, Coating, Enameling, Copper Plating          | [24, 33, 34]|
| Temporary Corrosion Resistance| They are used with the combined effect of cationic pipeline protection. Both the process at the cathode and anode must be effectively monitored | Protective coating, Desiccant method, VCI method                      | [24, 33, 34]|

8. Surface alloying
Two factors define corrosion rate; namely corrosion scale protection and corrosion scale coverage. The protection is directly proportional to the concentration of Cr in the corrosion scale, as the Cr content increase corrosion rate is reduced [43]. It was deduced from the experimental results conducted by David and Robert (2006), that, the alloying of carbon steel could enhance corrosion resistance above that of X70 steel [47]. From the tests conducted, the samples were exposed to different environmental condition (1% NaCl + NaHCO3—pH 4.5 (gas regime) and Forties brine—Ph 5.6 (oil regime)), the result shows that of all the alloy used (Si, Mo, Cr, V, Cu Mn), Cr was more effective; which is as a result of the protective surface film developed that opposes the corrosion reaction; this film is of ∼50–100 μm uniform thickness and made up of 3% Cr [47].

9. Conclusion

The damage caused by corrosion cannot be ignored, guarding against it should be of paramount importance to every material engineer. A failed pipeline poses a severe risk to humanity and the environment, hence developing a material (Dual Phase Steel) with improved corrosion and wear resistance is a necessity. Having considered different methods of mitigating against corrosion, it would, therefore, be concluded that, the choice of UIT combined with EDSA by Cr on low carbon steel will effectively improve corrosion and wear resistance of surface layer of pipelines.

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