

ACCEPTED MANUSCRIPT

Mitigating the effect of corrosion and wear in the application of High Strength low Alloy Steels (HSLA) in the petrochemical transportation industry - a review

To cite this article before publication: Emmanuel Olorundaisi *et al* 2019 *Mater. Res. Express* in press <https://doi.org/10.1088/2053-1591/ab65e7>

Manuscript version: Accepted Manuscript

Accepted Manuscript is “the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an ‘Accepted Manuscript’ watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors”

This Accepted Manuscript is © 2019 IOP Publishing Ltd.

During the embargo period (the 12 month period from the publication of the Version of Record of this article), the Accepted Manuscript is fully protected by copyright and cannot be reused or reposted elsewhere.

As the Version of Record of this article is going to be / has been published on a subscription basis, this Accepted Manuscript is available for reuse under a CC BY-NC-ND 3.0 licence after the 12 month embargo period.

After the embargo period, everyone is permitted to use copy and redistribute this article for non-commercial purposes only, provided that they adhere to all the terms of the licence <https://creativecommons.org/licenses/by-nc-nd/3.0>

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions will likely be required. All third party content is fully copyright protected, unless specifically stated otherwise in the figure caption in the Version of Record.

View the [article online](#) for updates and enhancements.

Mitigating the Effect of Corrosion and Wear in the Application of High Strength Low Alloy Steels (HSLA) in the Petrochemical Transportation Industry -A Review

¹E. Olorundaisi, ¹T. Jamiru, ¹A.T. Adegbola, ¹

¹Department of Mechanical Engineering, Mechatronics, and Industrial Design, Tshwane University of Technology, Pretoria, South Africa.

E-mail: Corresponding author: olorundaisiemmanuel@gmail.com

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.

Keywords: Petrochemical, High Strength Low Alloy Steels, Corrosion, Wear

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.

2. Classification of HSLA Steel

Several factors such as; composition, properties, method of manufacturing, microstructure, strength, heat treatment, etc. determine the classification of HSLA Steel. It is one of the most used materials around the globe with a carbon content ranging from 0.2 to 2.1 wt% ⁵. HSLA is classified as shown in table 1. These steels are developed for various numbers of important applications where high strength, corrosion resistance, wear resistance, ductility, toughness, and low cost are important ⁶⁻¹¹.

Table 1: Classification of Steel ⁶⁻¹³

Type	Characteristics	Application	Reference
Weathering steels	Presence of little quantities of alloying elements for strengthening and improving corrosion resistance, without the need for painting	Pipelines, earthmoving machines	3,8
Micro-alloyed ferrite-pearlite steels	Contain little percentage of carbide (carbonitride forming element), vanadium, niobium, titanium for refinement of grain, the transformation of controlled temperature and strengthening.	Petrochemical transportation, Construction, Bearings	14,15
As-rolled pearlitic steels	Contain carbon-manganese with some alloying elements for strengthening, formability, toughness, and weldability.	High-strength wires and high-strength tee rails	7,11
Acicular ferrite (low-carbon bainite) steels	Contain a little percentage of carbon (<0.5%); it is of high yield strength, improved toughness, formability, and weldability.	Pipelines	8
Dual-phase steels	It is made up of martensite with a dispersed ferritic matrix; it has good ductility and high tensile strength.	Automobile,	16,17

3. Corrosion in Petrochemical Transportation

For several years, CO₂ and H₂S 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, CO₂ and H₂S, water, flow velocity, water, and oil wetting, surface, and composition of the steel 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 CO₂ ²¹. Among the impurities (H₂O, SO₂, NO₂, O₂, and H₂S) contained in CO₂, H₂O plays an important role in the corrosiveness of the material, its presence formed solubility limit in a supercritical state (SC CO₂). However, due to the fluctuation of temperature and pressure, while transporting and injecting CO₂, H₂O 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 protection²⁴.

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 refers to as contaminants²⁵. 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 crude water or fuel is another cause of crude corrosiveness²⁵. Crude corrosiveness is expressed in terms of the Total Acid Number (TAN), Total Sulfur Content (TSC), micro-organisms, salt and water content²⁵. 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 CO₂, H₂S, H₂O, organic acid and mercury could cause corrosion, hence CO₂ and H₂S in natural gas dissolve in water to form an acid that aids corrosion²⁵. Sweet corrosion is the result of CO₂ while sour corrosion is caused by the presence of H₂S.

4 Agents of Corrosion

Corrosion of steel is stimulated by several agents, such as CO₂, H₂O, O₂, 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 CO₂, dry CO₂ gas is not corrosive until it's been dissolved in an aqueous solution through which it enables electrochemical reaction, as seen in equation 1²⁶.



Likewise, is the presence of hydrogen sulfide H₂S 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 3²⁶.



Another agent of corrosion is bacteria from microbiological organisms, which produce waste such as CO₂, H₂S 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 4-7²⁶⁻²⁹.



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.



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



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 CO₂ in water and is one of the most identified problems in the petrochemical industry. Dissolving dry CO₂ gas in aqueous solution promotes electrochemical reactions, between the metal and the solution^{26,30,31}.

ii. Sour Corrosion

When hydrogen sulfide (H₂S) is dissolved in water, it leads to sour corrosion. The reaction that takes place between the H₂S and water formed a weak acid, which leads to pipeline embrittlement. The forms of sour corrosion are uniform, pitting, and stepwise cracking^{26,30,31}.

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^{26,30,31}.

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^{26,30,31}.

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^{26,30,31}.

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^{26,30,31}.

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 it²⁶.

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 material²⁶.

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 ^{26,32-35}.

- 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.

Table 2: Corrosion Resistance ^{24,36-39}.

Corrosion Resistance	Characteristics	Example	Reference
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	38,39
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	24,36
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	24,36,37
Temporary Corrosion Resistance	They are used with the combined effect of cathodic pipeline protection. Both the process at the cathode and anode must be effectively monitored	Protective coating, Desiccant method, VCI method	24,36,37

8 Surface Alloying

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 achieved using Ultrasonic impact treatment (UIT) or Electric discharge and Surface alloying (EDSA)⁴⁰. 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 improved⁴. 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 surface⁴¹. 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^{41,42}.

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)⁴³. 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 of degradation that could end in failure of the casing and pipelines⁴⁴. Mitigating against this required infusing Cr into the material for better material with good resistance to wear and corrosion^{19,20,45}.

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 factor⁴. 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^{44,46}. 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 resistance⁴⁷. 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 3-10⁴⁷.

Table 3: Influence of some Alloy Element^{45,48-50}

Alloy Element	Characteristics
Carbon	Influence the properties (hardenability, strength) and microstructure of the material.
Manganese	It hardened, improve the surface quality and weldability
Silicon	Deoxidation while melting
Phosphorous	Reduces ductility

Sulfur	Reduces ductility
Niobium	Enhanced notch toughness
Vanadium	Refine ferrite phase
Titanium	Restricts grain growth
Zirconium	Added to improve inclusion properties
Copper	Enhanced corrosion resistance
Nickel Additions	Improve Ferrite Phase, corrosion resistance and strengthen structural applications
Chromium Additions	Improved hardness, corrosion, wear, and abrasion resistance
Molybdenum Additions	Increases fracture toughness, reduces the transformation of austenite to martensite

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 ⁴⁷. It was deduced from the experimental results conducted by David & Robert (2006), that, the alloying of carbon steel could enhance corrosion resistance above that of X70 steel ⁵¹. 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 ⁵¹.

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.

Acknowledgment

The fund provided by the National Research Foundation (NRF) program, South Africa, is greatly appreciated.

Reference

1. Keeler S, Menachem K, Peter J M. Advanced high-strength steels application guidelines V6. World Auto Steel. In: *World Auto Steel*. ; 2016:3-80.
2. ASM HC. High-Strength Structural and High-Strength Low-Alloy Steels. In: *Properties and Selection: Irons, Steels, and High-Performance Alloys*. ; 2018:389-423. doi:10.31399/asm.hb.v01.a0001025
3. Uemori R, Hasegawa Y, Hara T, et al. Steels for energy production and transport. *Nippon Steel Tech Rep*. 2012;(101):68-78.
4. Mordyuk BN, Prokopenko GI, Grinkevych KE, Piskun NA, Popova T V. Effects of ultrasonic impact treatment combined with the electric discharge surface alloying by molybdenum on the surface related properties of low-carbon steel G21Mn5. *Surf Coatings Technol*. 2017;309:969-979. doi:10.1016/j.surfcoat.2016.10.050
5. IMTISAL-E-NOOR. Steel making flow chart : https://www.academia.edu/5560166/classification_of_steel. Published 2011.
6. Han K, Edmonds D V., Smith GDW. Optimization of mechanical properties of high-carbon pearlitic steels with Si and V additions. *Metall Mater Trans A Phys Metall Mater Sci*. 2001;32(6):1313-1324. doi:10.1007/s11661-001-0222-7
7. Taleff EM, Lewandowski JJ, Poursadian B. Microstructure-property relationships in pearlitic eutectoid and hypereutectoid carbon steels. *Jom*. 2002;54(7):25-30. doi:10.1007/BF02700982
8. Microstructure FD. Study of Pipeline Steels with Acicular Ferrite Microstructure and. 2015;18(1):36-41.
9. Saha A, Mondal DK, Biswas K, Maity J. Development of high strength ductile hypereutectoid steel by cyclic heat treatment process. *Mater Sci Eng A*. 2012;541:204-215. doi:10.1016/j.msea.2012.02.026
10. Sas J, Kvackaj T, Milkovic O, Zemko M. Influence of hot plastic deformation in γ & ($\gamma + \alpha$) area on the structure & mechanical properties of high strength low alloyed (HSLA) steel. *AES-ATEMA Int Conf Ser - Adv Trends Eng Mater their Appl*. 2016;Part F1243(i):53-61. doi:10.3390/ma9120971
11. Han K, Mottishaw TD, Smith GDW, Edmonds D V. Effects of vanadium addition on nucleation and growth of pearlite in high carbon steel. *Mater Sci Technol (United Kingdom)*. 1994;10(11):955-963. doi:10.1179/mst.1994.10.11.955
12. Wiczerzak K, Bala P, Stepien M, Cios G, Koziel T. Formation of eutectic carbides in Fe-Cr-Mo-alloy during non-equilibrium crystallization. *Mater Des*. 2016;94:61-68. doi:10.1016/j.matdes.2016.01.028
13. Han K, Mottishaw TD, Smith GDW, Edmonds D V., Stacey AG. Effects of vanadium additions on microstructure and hardness of hypereutectoid pearlitic steels. *Mater Sci Eng A*. 1995;190(1-2):207-214. doi:10.1016/0921-5093(94)09604-U
14. Morales EV. *ALLOY STEEL – PROPERTIES AND USE*. (Morales EV, Smiljanic T, eds.). Janeza Trdine 9, 51000 Rijeka, Croatia Copyright: InTech; 2011.
15. Rashid MS. High-strength, low-alloy steels. *Science (80-)*. 1980;208(4446):862-869. doi:10.1126/science.208.4446.862
16. Olorundaisi E, Jamiru T, Adegbola TA. Mechanical and microstructural evaluation of dual phase steel, quenched in bitumen and water at an intercritical temperature: effect of holding time. *Mater Res Express*. 2019;6(11):115606. doi:10.1088/2053-1591/ab4747

17. Olorundaisi E, Jamiru T, Adegbola TA, Ogunbiyi OF. Modeling and optimization of operating parameters using RSM for mechanical behaviour of dual phase steels. *Mater Res Express*. 2019;6(10):105628. doi:10.1088/2053-1591/ab430e
18. Perez TE. Corrosion in the oil and gas industry: An increasing challenge for materials. *Jom*. 2013;65(8):1033-1042. doi:10.1007/s11837-013-0675-3
19. Koteeswaran M. Co₂ and H₂S Corrosion in Oil Pipelines. *Nature*. 1971;232(5305). doi:10.1038/232009a0
20. López DA, Schreiner WH, De Sánchez SR, Simison SN. The influence of carbon steel microstructure on corrosion layers: An XPS and SEM characterization. *Appl Surf Sci*. 2003;207(1-4):69-85. doi:10.1016/S0169-4332(02)01218-7
21. Abd El-Lateef HM, Abbasov VM, Aliyeva LI, Ismayilov TA. Corrosion Protection of Steel Pipelines Against CO₂ Corrosion-A Review. *Chem J*. 2012;02(02):52-63.
22. Wei L, Gao K, Li Q. Corrosion of low alloy steel containing 0.5% chromium in supercritical CO₂-saturated brine and water-saturated supercritical CO₂ environments. *Appl Surf Sci*. 2018;440(May):524-534. doi:10.1016/j.apsusc.2018.01.181
23. Al-Sultani KF, Abdulsada SA. Improvement Corrosion Resistance of Low Carbon Steel by Using Natural Corrosion Inhibitor. *Int J Adv Res*. 2013;1(4):239-243.
24. Hagarová M, Cervová J, Jaš F. Selected types of corrosion degradation of pipelines. *Koroze a Ochr Mater*. 2015;59(1):30-36. doi:10.1515/kom-2015-0010
25. Groysman A. Corrosion problems and solutions in oil, gas, refining and petrochemical industry. *Koroze a Ochr Mater*. 2017;61(3):100-117. doi:10.1515/kom-2017-0013
26. Cicek V. Corrosion in Petroleum Industry. *Corros Eng Cathodic Prot Handb*. 2017;2016(Part I):171-176. doi:10.1002/9781119284338.ch27
27. Prof. K. A. Natarajan. Advances in Corrosion Engineering. NPTEL Web Course. <https://nptel.ac.in/courses/113108051/>. Published 2012.
28. Mandar K. Corrosion in Marine Environment. *Corros Environ Ind*. 2018:42-60. doi:10.31399/asm.hb.v13c.a0004106
29. Lister DH. Corrosion for Engineers. *Corros Eng*. 1967;1(6):1. doi:10.1016/B978-008044495-6/50013-6
30. Fortana M., Mita M. The Eight forms of corrosion and the corrective measures. eprints.nmlindia.org/3414/1/137-148.PDF. Published 1953.
31. Cabussú MS. Basic Causes of Corrosion. http://www.bu.edu.eg/portal/uploads/discussed_thesis/11018107/11018107_I.pdf. Published 2015.
32. Hansson CM. The impact of corrosion on society. *Metall Mater Trans A Phys Metall Mater Sci*. 2011;42(10):2952-2962. doi:10.1007/s11661-011-0703-2
33. The Effects and Economic Impact of Corrosion. ASM International. https://www.asminternational.org/documents/10192/1849770/06691G_Chapter_1.pdf. Published 2000.
34. Yang L, Hort N, Willumeit R, Feyerabend F. Effects of corrosion environment and proteins on magnesium corrosion. *Corros Eng Sci Technol*. 2012;47(5):335-339. doi:10.1179/1743278212Y.0000000024
35. Davis JR, Associates D and. The Effects and Economic Impact of Corrosion. *Corros Underst*

- 1
2
3 *Basics*. 2000:1-21. doi:10.1016/S0257-8972(02)00586-8
- 4
5 36. Tait WS. *Corrosion Prevention and Control of Chemical Processing Equipment*. Second Edi.
6 Elsevier Inc.; 2005. doi:10.1016/B978-081551500-5.50029-X
- 7
8 37. Tait WS. *Controlling Corrosion of Chemical Processing Equipment*. Third Edit. Elsevier Inc.;
9 2018. doi:10.1016/B978-0-323-52472-8.00028-9
- 10
11 38. Ramachandran S. Corrosion inhibitors-advancements in testing. *Trends Oil Gas Corros Res*
12 *Technol Prod Transm*. 2017;455-469. doi:10.1016/B978-0-08-101105-8.00019-X
- 13
14 39. Dariva CG, Galio AF. *Corrosion Inhibitors - Principles Mechanisms and Applications*. intech
15 open Science; 2014. doi:http://dx.doi.org/10.5772/57255
- 16
17 40. Yu J, Gou G, Zhang L, Zhang W, Chen H, Yang YP. Ultrasonic Impact Treatment to Improve
18 Stress Corrosion Cracking Resistance of Welded Joints of Aluminum Alloy. *J Mater Eng*
19 *Perform*. 2016;25(7):3046-3056. doi:10.1007/s11665-016-2087-3
- 20
21 41. Mordyuk BN, Prokopenko GI, Volosevich PY, Matokhnyuk LE, Byalonovich A V., Popova T
22 V. Improved fatigue behavior of low-carbon steel 20GL by applying ultrasonic impact
23 treatment combined with the electric discharge surface alloying. *Mater Sci Eng A*.
24 2016;659:119-129. doi:10.1016/j.msea.2016.02.036
- 25
26 42. Lesyk DA, Martinez S, Mordyuk BN, et al. Microstructure related enhancement in wear
27 resistance of tool steel AISI D2 by applying laser heat treatment followed by ultrasonic impact
28 treatment. *Surf Coatings Technol*. 2017;328:344-354. doi:10.1016/j.surfcoat.2017.08.045
- 29
30 43. Monteiro WA, Buso SJ, da LV. Application of Magnesium Alloys in Transport. *New Featur*
31 *Magnes Alloy*. 2012;(April 2016). doi:10.5772/48273
- 32
33 44. Guo S, Xu L, Zhang L, Chang W, Lu M. Characterization of corrosion scale formed on 3Cr
34 steel in CO₂-saturated formation water. *Corros Sci*. 2016;110:123-133.
35 doi:10.1016/j.corsci.2016.04.033
- 36
37 45. Cotton J. Steels for Oil and Gas Applications. Engineering Solution. [http://www.one-eighty-](http://www.one-eighty-degrees.com/)
38 [degrees.com/](http://www.one-eighty-degrees.com/). Published 2011.
- 39
40 46. Carvalho DS, Joia CJB, Mattos OR. Corrosion rate of iron and iron – chromium alloys in CO₂
41 medium. 2005;47:2974-2986. doi:10.1016/j.corsci.2005.05.052
- 42
43 47. Li W, Xu L, Qiao L, Li J. Effect of free Cr content on corrosion behavior of 3Cr steels in a CO
44 2 environment. *Appl Surf Sci*. 2017;425:32-45. doi:10.1016/j.apsusc.2017.06.320
- 45
46 48. Wang E, Sun DJ, Liu H, et al. The Oxidation Behavior of Ni–15Cr–5Al–xSi (x = 0, 1, 3, 5
47 wt%) Alloys in Air at 1100 °C. *Oxid Met*. 2019;(0123456789). doi:10.1007/s11085-019-
48 09922-0
- 49
50 49. Guo YY, Zhang J, Li KF, et al. Corrosion behaviour of Fe-6.5 wt-%Si atomised powders.
51 *Corros Eng Sci Technol*. 2013;48(3):230-233. doi:10.1179/1743278213Y.0000000086
- 52
53 50. Li W, Han K, Niu R, Liang T, Lai C, Zhang X. Effect of Si and Y₂O₃ Additions on the
54 Oxidation Behavior of Ni–xAl (x = 5 or 10 wt%) Alloys at 1150 °C. *Oxid Met*. 2018;89(5-
55 6):731-753. doi:10.1007/s11085-017-9814-5
- 56
57 51. Edmonds D V., Cochrane RC. The effect of alloying on the resistance of carbon steel for
58 oilfield applications to CO₂ corrosion. *Mater Res*. 2006;8(4):377-385. doi:10.1590/s1516-
59 14392005000400004
- 60