Erosion enhanced corrosion and corrosion enhanced erosion of API X-70 pipeline steel

Md. Aminul Islam [a,*], Zoheir N. Farhat [a], Elsadig M. Ahmed [b], A.M Alfantazi [c]

[a] Department of Process Engineering and Applied Science, Materials Engineering Program, Dalhousie University, Halifax, Nova Scotia, Canada B3 J 2X4
[b] Mechanical and Industrial Engineering Department, College of Engineering, Qatar University
[c] Department of Metals and Materials Engineering, University of British Columbia, Vancouver, BC, Canada V6T 1Z4

A B S T R A C T

Erosion–corrosion is common in oil and gas processing plants and pipelines where there is interaction between solid particles, corrosive fluid and target material. In this study, the synergism between erosion and corrosion of API pipeline steel has been assessed under liquid–solid impingement conditions in 2 g/l NaCl solution purged with CO_2 as the corrosive media and aluminum oxide as the erodent. The total material loss rate and the components of erosion, corrosion and their synergistic interactions have been determined. A test setup was designed to mitigate the limitations of the in situ method (to avoid the fluctuation in electrochemical data due to bubble formation and turbulence). The flow velocity was varied from 36 to 81 m s^{-1}, while angle of incidence was kept constant at 90°. The experimental results show that there is an immense correlation exists between erosion and corrosion. It was observed that erosion enhances corrosion and corrosion enhances erosion with each contributing to significant synergism.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

Hydro-transport system (pipelines) transports oil sands from excavation to the extraction plants, refineries and consumer-ready products to markets. During the transportation process metal surface is exposed to flowing corrosive environment which causes erosion–corrosion, in which, the mechanical process of metal removal through erosion and the electrochemical process of corrosion are coupled [1,2]. The resulted mass loss is higher than the summation of mass loss due to pure erosion and pure corrosion and the interaction between these two processes have been referred by different researchers as 'synergistic' effect [3,4]. Corrosion of carbon steel in CO_2 environment has been a continuing problem in oil and gas industries. As the oil and gas emerge from the geological formation they are always accompanied by some water and varying amount of 'acid gases', carbon dioxide (CO_2). Several investigations [5–14] have been reported to study the erosion–corrosion phenomena involved.

The problem caused by the interaction of erosion and corrosion is severe and the mechanism of synergy is not thoroughly understood because of its complexity. Postlethwaite [15] pointed out that corrosion increases erosion rate by roughening the metal surface because erosion is sensitive to the impingement angle of solid particles. Matsumura et al. [16] agreed that the increase in the surface roughness would play a role in synergism but they suggested that erosion can be enhanced by corrosion through the elimination of the work-hardened layer. Recently, Li et al. [1] proposed that localized attack causes disruptions in the surface oxide film (caused by the particle impacts) which enhances crack growth. Oxide flakes then detach leading to increased erosion.

Hu and Neville [17] studied CO_2 erosion–corrosion behavior of API X-65 steel in oil and gas environment. In situ electrochemical linear polarization measurements were conducted (mixture of fluid and sand particles were delivered through a dual nozzle system impinging on to a flat specimen surface) to determine the contributions to total degradation due to corrosion. They found that surface degradation due to corrosion process reduce the resistance to erosion which is the most significant damage process during erosion–corrosion. Burstein et al. [4] proposed that the effect of corrosion on slurry erosion is mainly through detachment of the flakes formed by repeated impacts of solid particles. It has also been reported that corrosion is almost doubled in the presence of erosion. This observation supports previous speculation [2,18] that erosion affects corrosion by increase of local turbulence/mass transfer and by surface roughening. Malka et al. [19] investigated the interaction between erosion and corrosion of AISI 1018 carbon steel to quantify the synergism in flow environments. The test cell was segmented in order to enable local electrochemical and weight loss measurements across the flow disturbances and it was found that corrosion and erosion enhance one another resulting in significant synergism.

* Corresponding author. Tel.: +1 902494 3745; fax: +1 9024207639.
E-mail addresses: Md.Aminul.Islam@Dal.Ca,
niljochhona@gmail.com (Md. Aminul Islam).

Xie et al. [20] showed that by increasing frequency of intermittent erosion–corrosion cycle, it is possible to obtain close results as if erosion–corrosion happened together. This test method provides more stable electrochemical measurements and is employed to mitigate the limitations of the in situ method [17,19], which is the difficulty of controlling fluctuation in electrochemical data due to bubble formation and turbulence. This study focuses on understanding the erosion–corrosion mechanisms on API X-70 pipe line steel and the constitutions of total material loss in term of erosion, corrosion and their interactions. A test setup was designed to avoid the fluctuation in electrochemical data due to bubble formation and turbulence. Although the environmental conditions that the pipeline materials are exposed to in real application are often inconsistent/less reliable than laboratory monitoring systems, the objective of current work is to improve the understanding of erosion–corrosion predictions by identifying critical parameters.

2. Methodology

The presence of CO_2 leads to the formation of a weak carbonic acid (H_2CO_3) which drives the carbonate/bicarbonate (CO_3^{2-}/ HCO_3^-) corrosion reactions. This initiating step is represented by the reaction:
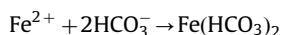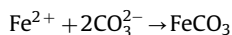
$$CO_2 + H_2O \leftrightarrow H_2CO_3$$
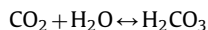
The subsequent corrosion process is controlled by three cathodic reactions and one anodic reaction [21]. Cathodic reactions include the reduction of carbonic acid into bicarbonate ions, reduction of bicarbonate ions into carbonate ions and the reduction of hydrogen ions to hydrogen gas:

$$2H_2CO_3 + 2e^- \rightarrow H_2 + 2HCO_3^-$$

$$2HCO_3^- + 2e^- \rightarrow H_2 + 2CO_3^{2-}$$

$$2H^+ + 2e^- \rightarrow H_2$$
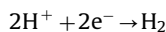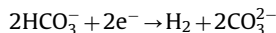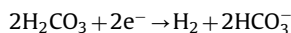
In carbonate/bicarbonate media anodic reaction involves oxidation of iron to ferrous (Fe^{2+}) ion:

$$Fe \rightarrow Fe^{2+} + 2e^-$$
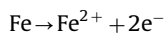
These corrosion reactions provide a chemical environment which promotes the formation of iron carbonate ($FeCO_3$), where ferrous ions react directly with carbonate ions. It can also form by a two-step process when ferrous ions react with bicarbonate ions, iron bicarbonate forms, which subsequently dissociate into iron carbonate along with carbon dioxide and water [22]:

$$Fe^{2+} + 2CO_3^{2-} \rightarrow FeCO_3$$

$$Fe^{2+} + 2HCO_3^- \rightarrow Fe(HCO_3)_2$$

$$Fe(HCO_3)_2 \rightarrow FeCO_3 + CO_2 + H_2O$$

The significance of $FeCO_3$ formation is that it drops out of solution as a precipitate due to its limited solubility [22]. This precipitate has the potential to form passive film on the surface of steel which may reduce corrosion.

The combined effects of erosion and corrosion can lead to different modes of degradation on the material surface, it is important to separate the erosion, corrosion and interaction between these processes. Various techniques [23,24] have been used by different researchers to quantify these components which facilitate the analysis of material loss mechanisms and development of predictive models [25–29]. The total material loss during erosion–corrosion process can be defined as [30,31]

$$T = E_0 + C_0 + S \tag{1}$$

where T is the total mass loss rate of the material, E_0 is the erosion rate in the absence of corrosion, C_0 is the corrosion rate in the absence of erosion and S is the synergistic component and is defined as

$$S = \Delta C_E + \Delta E_C \tag{2}$$

where

$$\Delta C_E = C_E - C_0 \tag{3}$$

$$\Delta E_C = E_C - E_0 \tag{4}$$

ΔC_E is the change in corrosion rate due to erosion and ΔE_C is the change in erosion rate due to corrosion, E_C is the total erosion component in the presence of corrosion and C_E is the total corrosion component in the presence of erosion.

3. Experimental

3.1. Materials

API X-70 steel coupons were used as test specimens and aluminum oxide particles were used as erodent in all erosion and corrosion experiments. The physical and chemical properties of the specimen and erodent are given in Table 1.

3.2. Surface characterization

In order to achieve uniformity and adequate surface finish, specimens (15.8 mm diameter and 6.3 mm thick) were grounded using 240, 320, 400 and 600 grit SiC abrasive papers and then polished using 1 µm, 0.3 µm and 0.05 µm gamma alumina suspension prior to experiments.

Table 1
Physical and chemical properties of API X-70 and aluminum oxide.

API X-70		Aluminum oxide	
Yield strength	482 MPa	Crystal phase	Alpha
Elongation	17%	Specific gravity	3.95 g/cc
Density	7.84 g/cm^3	Melting point	2,000 °C
Hardness	200 Knoop	Hardness	2000 Knoop
Grain size	2–5 µm	Particle size	240 Grit/70 µm

Composition of API X-70						Composition of aluminum oxide					
Fe	C	Mn	P	S	Si	AlO$_2$	TiO$_2$	SiO$_2$	Fe	MgO	Alkali
balance	0.06	1.2	0.01	0.005	0.24	99.5	0.099	0.05	0.08	0.02	0.30