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Correlation between surface-hardness degradation and erosion resistance of carbon steel—Effects of slurry chemistry

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ABSTRACT

The paper studied the effects of slurry chemistry on erosion of carbon steel. According to experimental measurements, the erosion rate in corroding slurries was a linear function of logarithm of anodic current density. In near-neutral or alkaline slurries, the erosion rates are independent of solution chemistry while the erosion rates in the acidic slurries were sensitive to slurry chemistry. To investigate the underlying mechanism, the *in-situ* surface hardness in corroding environments was measured with the nano-indentation technique under galvanostatic control. The results indicated that the surface hardness would decrease as anodic current was applied. The surface hardness degradation in near-neutral or alkaline electrolytes were almost unaffected by solution chemistry but that in acidic electrolyte depended heavily on solution chemistry. A linear correlation between the accelerated erosion and surface hardness degradation indicated that corrosion-induced surface-hardness degradation would be the dominant mechanism of corrosion-enhanced erosion.

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1. Introduction

Erosion–corrosion is a significant issue for the oil sands industry in Northern Alberta, Canada, where handling and processing of essentially silica-based solids results in material loss with an unacceptably high rate [1]. Mechanical erosion and electrochemical corrosion are the basic mechanisms of material loss. The former is regarded as the phenomenon that metallic material is removed mechanically from a surface in the form of debris before it is ionized, as a result of plastic deformation and rupture of material in the surface layer. The latter describes ionization of metallic atoms before they leave the surface, so that the corresponding wastage can be correlated to the corrosion current density via Faraday's law. The total material loss rate \dot{w} is the sum of material loss rates caused by erosion \dot{e} and corrosion \dot{c} ,

$$\dot{w} = \dot{e} + \dot{c} \quad (1)$$

The experimental measurements demonstrated clearly that erosion and corrosion in flowing slurry would enhance each other [2–5]. The corrosion of metallic materials in the erosive slurries can be accelerated by the depassivation [5–8] or dynamic plastic strain [4,9], due to the solid particle impingement. The effect of erosion-enhanced corrosion in carbon steel pipes for tailing slurry transportation in the oil sand production is not significant because corrosion scale is non-protective [9]. Although corrosion often is responsible for only a small fraction of

total material loss [9–12], it can lead to a significant increase of erosion rate [2,4,9]. This phenomenon is termed corrosion-enhanced erosion. The additional material loss caused by the corrosion-enhanced erosion \dot{e}_c is defined by

$$\dot{e}_c = \dot{e} - \dot{e}_0 \quad (2)$$

where \dot{e} and \dot{e}_0 are the erosion rates measured in corrosive slurry and under cathodic protection, respectively.

Mechanism of corrosion-enhanced erosion is very complex because it is affected by multiple interactions of various factors [2,8,13], including the hydrodynamic parameters [8,12–14], the characteristics of erodent [15,16], temperature [3], corrosivity of slurries [17,18], the metallurgical features [19,20], the mechanical and corrosion behaviour of target material [2,8,13,21]. Stack and her colleagues [3,8,13,16,22] made a lot of efforts to build erosion–corrosion maps for various materials to illustrate the dependence of erosion–corrosion mechanisms/performance on the combinations of environmental and hydrodynamic parameters. Depending on the test conditions, the erosion rate experimentally measured may be very different. As is summarized by Finner et al. [23], for example, erosion rate tends to increase with reduced hardness for pure metals but not for steels. Hutchings [24] proposed to correlate the erosion rate to the micro-hardness of steels measured on the eroded surface. An alternative explanation is the high strain rate created by solid particle impingement may play a role [24], so that the erosion models based on the dynamic hardness were proposed [25,26]. The impingement velocity of particles during slurry erosion is relatively low. Wood [2] reported slurry erosion rates measured from metallic and ceramic materials

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and found that the erosion rate was reduced with increasing hardness, no matter the materials were brittle or ductile. The corrosion-enhanced erosion is also affected by the corrosion mechanism. A recent experimental finding indicated that erosion rate of hypereutectic high chromium case iron in alkaline slurry decreased with increasing slurry velocity [27]. The abnormal high erosion rate at low slurry velocity was a result of localized corrosion that occurred at the carbide/matrix interface. Therefore, the development of a predictive model for erosion–corrosion requires a comprehensive understanding of effects of various factors involved in the erosion–corrosion.

During impingement in a corroding slurry at least two irreversible processes, electrochemical corrosion and plastic deformation, occur on the target surface concurrently, and these may enhance each other [4,28]. The fluxes resulting from the two irreversible processes are characterized by the anodic current density i_A and the plastic strain rate $\dot{\gamma}_p$, respectively. In the 1930s and 1940s, Resco [29] and Andrade [30] found the corroding environments that removed or alter the oxide film also promoted plastic deformation or creep of metals. Revie and Uhlig [31] reported the accelerated creep of copper wire when an anodic current was imposed. The phenomenon of corrosion-promoted creep has been observed in various other metals or alloys [30–32]. Gutman [32] interpreted this kind of chemo-mechanical interaction using the concept of irreversible thermodynamics and pointed out that anodic dissolution could increase the mobility of dislocations in a thin layer of material beneath the surface. The reduced resistance to plastic deformation in surface layer has been well demonstrated by the *in-situ* micro- and nano-hardness measurements [9,32–35]. This fact suggests that the impingement of a particle with identical momentum would create a larger crater in a corroding medium, resulting in a higher erosion rate [4,28,36–37]. Based on theories of irreversible thermodynamics, dislocation kinetics, materials strength and electrochemistry, the reduction of surface hardness due to the presence of anodic dissolution $\Delta H_v (< 0)$ can be formulated as follows [4,9,28,32]:

$$\frac{\Delta H_v}{H_v} = -B \log \left[\frac{i_A}{i_{th}} \right] \quad (3)$$

where H_v is the surface hardness measured in a non-corrosive environment, B is a constant related to the activation volume of dislocations and test conditions, i_A is the anodic current density; and i_{th} is the threshold current required to cause surface hardness degradation. Eq. (3) has been validated by the *in-situ* micro-hardness measurements [4,9,32,34].

Experimental evidence revealed that the surface hardness reduction induced by corrosion would result in the corrosion-enhanced erosion of carbon steel [4,9,34,35]. When the corrosion-induced surface hardness degradation is the sole mechanism of the corrosion-enhanced erosion, the normalized corrosion-enhanced erosion wastage, *i.e.*, the wastage ratio \dot{e}_c/\dot{e}_0 , is correlated to the anodic current density i_A by the following formula [4,9]:

$$\frac{\dot{e}_c}{\dot{e}_0} = Z \log \left(\frac{i_A}{i_{th}} \right) \quad (4)$$

where Z is an experimental constant. According to Eq. (4), the erosion will be accelerated when corrosion occurs concurrently and the normalized corrosion-enhanced erosion rate \dot{e}_c/\dot{e}_0 will increase linearly with the logarithm of anodic current density. The applicability of Eq. (4) has been experimentally validated [2,9,34]. However, the corrosion-enhanced erosion behaviour of a material is often complex and is impacted by various factors, such as, the facilities used in experiments [39], the hydrodynamics conditions [4,9] and the chemical compositions of slurries [17,18].

It has been observed in various metallic materials, including carbon or low alloy steels, pure iron, chrome white iron, brass and nickel alloys [13,18,39–41], that low pH slurry will result in a high rate of material loss under a given hydrodynamic condition. The corrosion of

these alloys is accelerated as the slurry pH is reduced. As predicted by Eq. (4), a higher anodic current density would lead to a higher erosion rate. In contrast, corrosion rate of aluminum is quite high in alkaline electrolyte owing to the dissolution of oxide surface film. Stack and Punwivat [22] found that erosion of aluminum was accelerated with increasing pH of slurries. The experiments mentioned above were conducted at the open circuit potentials (OCPs) [18,39,42,43] or potentiostatic control [13,44], where the corrosion and erosion rates would change simultaneously as the slurry pH varied. As such, it is technically difficult to insulate the impacts due to the change of corrosion rate and slurry chemistry. Based on the experimental data obtained under the free corrosion condition, we cannot quantify the correlation between the accelerated erosion and corrosion rate. The experimental evidence indicated that the adsorption of certain ion may affect the wear behaviour of target material *via* reducing the surface energy and altering the mechanical properties of surface layer [42]. Therefore, a further investigation into the impact of slurry chemistry on erosion–corrosion under well controlled conditions is helpful to provide more insights to the corrosion-enhanced erosion mechanisms.

2. Experimental methods

2.1. Erosion–corrosion tests

The test material was hot extruded rod of A1018 carbon steel with chemical composition in weight percent was 0.15–0.20 C, 0.60–0.90 Mn, < 0.05 P, < 0.05 S. Under the as-received condition, the microstructure was ferrite+small amount of pearlite. The thickness and outer diameter of the RCE (rotating cylinder electrode) specimens were 8 mm and 25 mm, respectively. The erosion–corrosion tests were conducted in slurries made using the solutions listed in Table 1. The erodent concentration of slurries was 428 kg/m³ (30 wt%). The erodent was underground silica sand provided by U.S. Silica Company, Ottawa. The size of sand particles was 50–70 mesh (300–212 μm) [9]. It was found in this study that the chemical composition of acidic slurries would affect erosion resistance. Hence, acidic solutions in four groups were selected for further exploring the effect of slurry chemistry. They were aqueous solutions of (1) 0.001 M to 0.1 M (pH 0.7–2.7) H₂SO₄; (2) Na₂SO₄ acidified with H₂SO₄, (pH 2–3); (3) 0.001 M to 0.1 M HCl (pH 1–3); and (4) NaCl acidified with HCl (pH 2–3).

A rotating cylinder electrode (RCE) system manufactured by Pine Instrument Ltd. was used in the erosion–corrosion tests. The

Table 1
Solutions for preparing slurries.

Catalogue	ID ^a	Solution composition
Neutral	N1	Deionized water
	N2	0.01 M Na ₂ SO ₄
	N3	0.1 M Na ₂ SO ₄
	N4	0.1 M NaCl
Basic	B1	0.01 M NaOH
	B2	0.01 M NaOH+0.1 M Na ₂ SO ₄
	B3	0.01 M NaOH+0.1 M NaCl
Acidic	A1	0.01 M H ₂ SO ₄
	A2	0.01 M H ₂ SO ₄ +0.1 M Na ₂ SO ₄
	A3	0.02 M HCl
	A4	0.02 M HCl+0.1 M NaCl

^a The solution ID without subscript represent the measurements obtained under anodic polarization with different applied current densities. The solution ID+subscript 'A' would represent that the measurement was performed under anodic polarization under galvanostatic control with $i_A = 1 \text{ mA/cm}^2$. The solution ID+subscript 'C' represented the measurement was conducted under cathodic protection.

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