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Erosion-enhanced corrosion of stainless steel and carbon steel measured electrochemically under liquid and slurry impingement

Z.B. Zheng, Y.G. Zheng*

Key Laboratory of Nuclear Materials and Safety Assessment, Institute of Metal Research, Chinese Academy of Sciences, 62 Wencui Road, Shenyang 110016, PR China

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ABSTRACT

The erosion-enhanced corrosion of 304 stainless steel and carbon steel under impingement by NaCl solution has been investigated. With increasing flow velocity, the open-circuit potential of carbon steel increases in the sand-free solution, while decreases in the sand-containing solution. The passive current density of stainless steel under impingement is close to that in quiescent condition in most cases, while increases by an order of magnitude at a flow velocity higher than the critical flow velocity. An ideal schematic has been used to explain the electrochemical results. The passivation of stainless steel under impingement is further analyzed by potentiostatic polarization.

1. Introduction

Erosion-corrosion has attracted a lot of attention in the past few decades because it is a general cause of material deterioration of flow-handing components such as impellers, turbines, pumps and pipes. Two different mass loss mechanisms are involved in the erosion–corrosion of metals, electrochemical corrosion and mechanical erosion. However, the total mass loss is usually larger than the sum of mass losses aroused by pure corrosion and pure erosion. The synergism or interaction between electrochemical corrosion and mechanical damage is responsible for it. Souza and Neville [1] have reported that the percentage of the interaction can be about 50% for a WC-Co-Cr HVOF coating under erosion-corrosion by 3.5% NaCl solution containing 1000 mg/l silica sands. Rajahram et al. [2] have discovered that the contribution of the interaction could be up to 60% for SS316L under erosion-corrosion in 0.3 M HCl solution containing sands. Zeng et al. [3] have investigated the erosion–corrosion behavior of X65 pipeline elbow and it can be calculated from the result that the interaction is beyond 50% of the total mass loss at most locations of the elbow. There is no doubt that the interaction between electrochemical corrosion and mechanical damage acts as an important role in erosion–corrosion and should be treated seriously.

Researches on the erosion-corrosion indicate that the percentage of the interaction is quite different based on the material system [4,5] and hydraulic condition [6–9], which makes the understanding of the interaction ambiguous. Actually, the interaction between electrochemical corrosion and mechanical damage consists of erosion-enhanced corrosion and corrosion-enhanced erosion. It is difficult to evaluate corrosion-enhanced erosion for the lack of effective methods. Therefore, the investigation on erosion-enhanced corrosion is quite significant in the study of interaction. In the flowing slurries, corrosion rate is affected by the forced convection and the impact of sand particle. The variations of mass transportation, cathodic reaction, passive behavior and anodic dissolved reaction may all determine the erosion-enhanced corrosion. For this reason, erosion-enhanced corrosion can be evaluated in situ by electrochemical methods. So far, electrochemical techniques have been widely used by researchers to study erosion-enhanced corrosion behavior. But the results usually turn out to be confused due to the complexity of the interaction. Wang and Stack [10] have carried out the potentiodynamic polarization curves of 304 stainless steel in a passive system containing sand particles and the result reveals that the corrosion potential increases with increasing flow velocity. However, it is reported by Ji et al. [11] that the corrosion potential of 304 stainless steel decreases with increasing flow velocity. It is really puzzling that the results are totally opposite in a similar environment. Additionally, the influences of flow velocity on passive current density are also inconsistent according to some researchers [12–16]. Passive current density may

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* Corresponding author. Fax: +86 24 23894149.
E-mail address: ygzheng@imr.ac.cn (Y.G. Zheng).

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Table 1
Chemical compositions of 304 stainless steel (304 s.s.) and A3 carbon steel (A3 c.s.) used in the experiment.

	Composition (wt.%)							
	Cr	Ni	Mn	S	P	Si	C	Fe
304 s.s.	17.38	8.13	1.074	0.004	0.034	0.53	0.024	Bal.
A3 c.s.	–	–	0.3 ∼ 0.8	<0.050	0.040	0.30	0.14 ∼ 0.22	Bal.

increase, decrease or even decrease in the first, and then increase with increasing flow velocity. The uncertain electrochemical result under erosion–corrosion may lead to a vague understanding on the erosion-enhanced corrosion.

In order to provide a clear insight into erosion-enhanced corrosion, passive film has been taken into account. It is believed that passive film is the main reason which distinguishes the erosion-corrosion behavior of passive material and non-passive material. Moreover, the different electrochemical results of passive material under different hydraulic conditions may also be ascribed to the behavior of passive film. According to some former studies [17–20], critical flow velocity is a critical parameter for the breakdown of passive film and a threshold where the transition from passive to erosion-corrosion regime starts for passive materials. It is a key factor which may affect erosion-enhanced corrosion significantly and it may be useful in clarifying the complex electrochemical results under erosion–corrosion. In this work, electrochemical techniques have been used to investigate the erosion-enhanced corrosion of a passive material 304 stainless steel and a non-passive material carbon steel under impingement by measurements of open-circuit potential, potentiodynamic polarization curves and potentiostatic curves. The parametric effects were investigated to determine the roles of sand particles and flow velocity on erosion-enhanced corrosion.

2. Experimental

Two kinds of materials used in the study were 304 stainless steel and A3 carbon steel which refers to ASTM A36 carbon steel. The chemical compositions of the two steels were given in Table 1. All samples were cut into 10 mm × 10 mm × 3 mm pieces. Each sample was sealed with epoxy, leaving an exposed working area of 1 cm^2. The working surface was ground with 240, 400, 600, and 1000 grid abrasive papers in sequence, degreased in alcohol, washed in distilled water and dried in air.

The test solution was a 3.5 wt.% NaCl solution without or with 4 wt.% sand particles (the concentration was calculated according to the mass of solution and the mass of sand particles which were added in before the test). The solution is near neutral with a pH of about 6.2. The sand particle was angularity with the sizes of 100–200 μm. The micrograph and particle size distribution of silica sand were presented in our former study [21].

The erosion–corrosion test was conducted using an impinging jet apparatus as described elsewhere [22]. A liquid jet from a nozzle of 3 mm in diameter was impacted onto the center of the test steels. The exit velocity of the jet was regarded as the flow velocity. The nozzle-to-specimen distance was kept constant at 5 mm. For all tests, the angle of impingement was 90°. The morphological observations of 304 stainless steel after impingement in different conditions were carried out by scanning electron microscopy (SEM) (FEI-Inspect F).

The in situ electrochemical measurements were measured using a three-electrode electrochemical cell comprising a standard saturated calomel reference electrode (SCE) and a platinum counter electrode. The standard saturated calomel electrode was connected to the cell via a Luggin probe. The electrodes were held steady during the impingement to avoid unexpected disturbance. All tests were conducted using potentiostat/galvanostat Gamry Interface 1000. Before tests, 304 stainless steel was initially pretreated cathodically at −1.2 V_{SCE} for 2 min to clean the surface [23,24]. Three types of electrochemical measurements were conducted in this work: open-circuit potential (OCP) test, potentiodynamic polarization test and potentiostatic test. During the OCP test, impingement started after a few seconds of immersion. Potentiodynamic polarization was conducted from −400 mV (vs. OCP) to 400 mV_{SCE} at a sweep rate of 0.5 mV/s. The potentiostatic current-time curves were measured by applying a constant anodic potential of −50 mV_{SCE}, which was selected in order to show the different anodic current densities of 304 stainless steel under impingement at different flow velocities. It would be seen from the potentiodynamic polarization curves that 304 stainless steel was in passive range at −50 mV_{SCE} in the solution. The flow velocities of 4, 7, 10 and 13 m/s were selected to conduct the experiments. All tests were repeated at least thrice.

3. Results

3.1. Critical flow velocity measurements

Potentiostatic test has been used to determine the critical flow velocity of 304 stainless steel under impingement by 3.5 wt.% NaCl solution containing 4 wt.% sand particles. The method has been proved effectively and efficiently to study the critical flow velocity of passive material in our former study [21].

The flow velocity applied in the potentiostatic test varies by time as shown in Fig. 1a. Fig. 1b and c show the responses of passive current density of 304 stainless steel at different flow velocities in NaCl solution without and with sand particles, respectively. When sand is absent, the variation tendency of current density is nearly smooth and the current density changes little with flow velocity over time. No obvious critical phenomenon has been observed in this condition. However, with the addition of sand particles in the solution, impingement gives rise to steps of current density at relatively high flow velocities. The current density steps up significantly and fluctuates intensively when the flow velocity increases stepwise. The result reveals that the critical flow velocity that separates the regions of non-observable and significant responses in this test is between 9 and 11 m/s for 304 stainless steel under impingement in 3.5 wt.% NaCl solution containing 4 wt.% silica sand particles.

3.2. Open-circuit potential measurements

Fig. 2 shows the open-circuit potentials as a function of time measured on A3 carbon steel under impingement at various flow velocities without (Fig. 2a) and with (Fig. 2b) sand particles. The rapid decrease of potential in the beginning declares that A3 carbon steel is in the state of active corrosion. As described in the part of experimental, impingement started after a few seconds of immersion. The instantaneous change of open-circuit potential can be recorded in the curve. It is apparent from the enlarged picture in Fig. 2a that all potentials jump positively due to the sudden start of impingement. Afterwards, the potentials decrease slowly and finally maintain at constant values of about −0.473, −0.463, −0.455 and −0.438 V_{SCE} until 5400 s at the flow velocities of 4, 7, 10 and 13 m/s, respectively. In other words, the final open-circuit potential increases with increasing flow velocity under impingement in the absent of sand particles. However, the dependence of open-circuit potential on flow velocity is quite different when the solution contains sand particles. The final potentials are about −0.445, −0.450, −0.463 and −0.465 V_{SCE} at the flow velocities of 4, 7, 10 and 13 m/s, respectively. Overall, the open-circuit potential of