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Short Communication

Visualising the dynamic processes of flow accelerated corrosion and erosion corrosion using an electrochemically integrated electrode array

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ABSTRACT

An electrochemically integrated and individually addressable multi-electrode array has been proposed and demonstrated as a new tool for simulating, visualising and monitoring the dynamic processes of flow accelerated corrosion (FAC) and erosion corrosion under natural corrosion conditions. It has been shown for the first time that FAC and erosion corrosion are able to evolve and propagate freely on the electrode array surface, and that similar corrosion patterns have been observed on the array and coupon surfaces after being exposed to the same flow condition. This method has enabled the visualisation of FAC and erosion corrosion processes with high spatial and temporal resolutions, providing a new means of probing, monitoring and assessing FAC and erosion corrosion and their prevention.

1. Introduction

Flow accelerated corrosion (FAC) and erosion corrosion are two challenging forms of localised corrosion that are affected by a complex combination of electrochemical, mass-transfer, fluid dynamic and mechanical factors [1–6], often acting synergistically and resulting in metal loss rates significantly higher than either erosion or corrosion acting alone [5,6]. Erosion corrosion is an electrochemical and mechanical process involving the impingement of particles, bubbles, or cavitation which cause corrosion and mechanical wear on the metal surface. While, FAC is distinct from erosion-corrosion and is primarily a corrosion process aided by chemical dissolution and mass transfer [7]. FAC often has a distinguishable corrosion pattern with a typical 'flow mark' [2,3], while erosion corrosion often has a crater-like appearance [1,4] due to mechanical impacts such as impingement of particles. FAC and erosion corrosion have been studied extensively in the past [1,4,8–12], however the probing and in situ monitoring of FAC and erosion corrosion under natural conditions remain a technological challenge. For instance FAC and erosion corrosion are believed to be significantly affected by competition between fresh metal surface generation through depassivation (local dissolution or breakdown of a normally insoluble oxide layer) and repassivation [9] due to combined local electrochemical, interfacial chemistry and confined mass transfer conditions, detailed understanding of these localised, dynamic and often complex processes are difficult because of the need for in situ monitoring of these processes.

Traditionally FAC and erosion corrosion are assessed in industry through periodic inspection using nondestructive test methods, electrical resistance probes [13] and iron concentration measurements [14]. In laboratory they are typically evaluated electrochemically employing methods such as current transient and potentiodynamic polarisation measurements, and devices such as rotating disc electrode [5,15,16] and slurry jet impingement loops [8–10]. For instance, Luo and co-workers have carried out extensive research on the erosion-enhanced corrosion of metals and alloys by detecting current transients caused by particle impact while holding the electrode in the passive potential range [4,9,17,18]. This method is very useful for understanding passive film breakdown and repassivation under anodic polarisation, however it is unable to do so under natural conditions because no current transient is detectable under the natural open circuit potential (OCP). In an effort to probe practical passive behaviour under OCP conditions, scratching electrodes were used to simulate the effect of sand impingement on corrosion process through the measurement of electrochemical noise generated during the scratching process [6,19]. The scratching technique also has a limitation since it only measures overall electrochemistry over the whole electrode surface rather than probing the localised electrode processes at the scratch. This illustrates limitations in traditional electrochemical methods for probing localised and dynamic interfacial processes, and the need for new technologies able to address these limitations.

Recently computational fluid dynamic simulation has been used in combination with multi-electrode array to study FAC of a simulated

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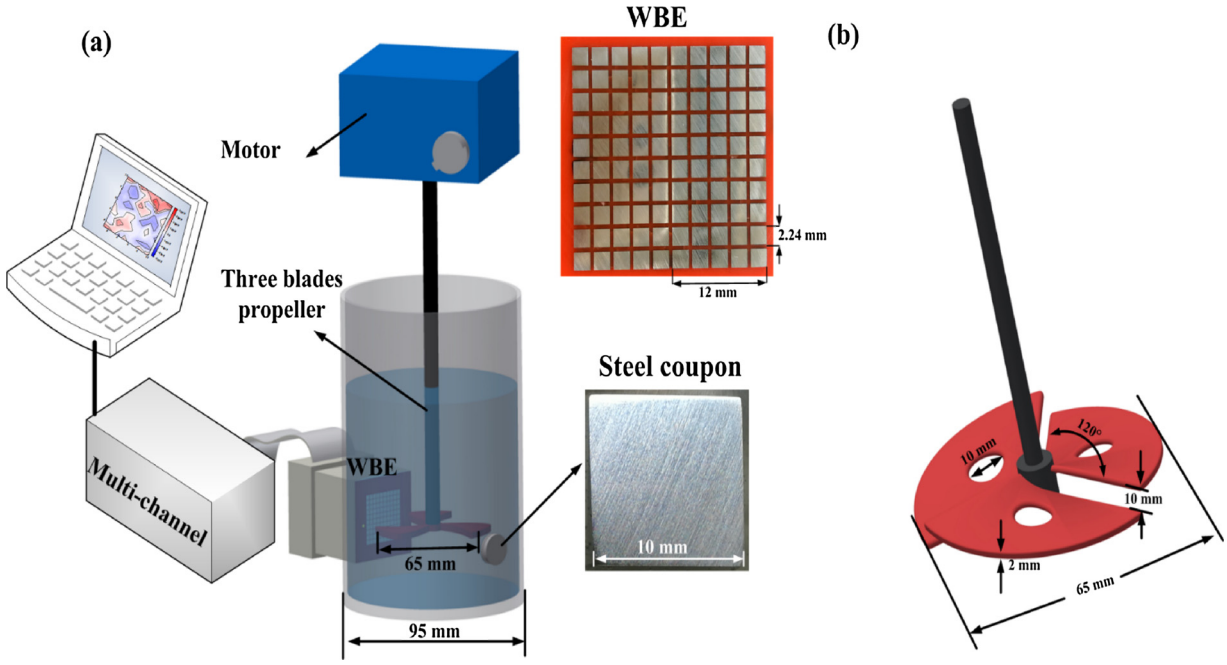

Fig. 1. Schematic diagram of the setup for FAC and erosion corrosion experiments.

pipeline elbow [20–22]. This innovative approach has enabled Zhang et al. to detect different corrosion behaviour due to varying hydrodynamics of fluid flow at the elbow [20–22]. It should be noted, however, that the electrode array used by Zhang et al. had a large inter-electrode spacing of approximately 6 mm between electrodes. Unfortunately, such a large inter-electrode spacing would lead to poor chemical interactions between electrodes located at different areas and therefore, as explained in a review of the electrode array method by Tan [23], insufficient electrochemical integration required for simulating FAC.

The ability of the electrode array in simulating a conventional one-piece electrode surface in FAC and erosion corrosion behaviour has not been explored to date. This work aims at pushing the frontier of the multi-electrode array method, often referred to as the wire beam electrode (WBE) [23–26], to addressing the difficult task of simulating and visualising the dynamic and complex FAC and erosion corrosion processes.

2. Material and methods

Fig. 1a shows a schematic diagram of the experimental setup in a cylinder-shaped electrochemical cell to generate flow dynamic conditions required for FAC and erosion corrosion experiments. A specially designed WBE and a steel coupon electrode are mounted in the test cell with the propeller positioned in the middle of their surfaces. The WBE consists of 100 closely packed but isolated square shaped electrodes of X65 pipeline steel (2.24 mm x 2.24 mm each) embedded in epoxy resin. The gaps between neighbouring electrodes were kept very small (0.2 ± 0.05 mm). Steel coupon was also made of the same steel with a surface dimension of 10 mm × 10 mm. The working surfaces of the WBEs and coupons were abraded with silicon carbide papers to 1200 grit finish and rinsed with acetone before installation in the cell. A three blades propeller with the diameter of 65 mm was installed in the middle of the cell for generating flow dynamic conditions. The geometrical parameter of the propeller is shown in Fig. 1b. The distance between the test sample and the edge of the propeller was about 9 mm. Sodium chloride solutions (NaCl, 0.5 M) without and with 10% sand particles (by weight) were used as the test fluids. The pH of the solution was approximately 6.8. The dissolved oxygen concentration was estimated to be 7.9–8.3 ppm at the test temperature of 23°C. As the test electrodes and coupons are close to the edge of the propeller, the Reynolds Number (Re) can be estimated using Eq. 1:

$$\mathrm{Re} = \frac{Nd^2}{v} \tag{1}$$

Where N is the rotating speed, d is the diameter of the propeller and v is the kinematic viscosity. It can be calculated that the Re was 4.4×10^5 and 8.8×10^5 in the 1000 rpm and 2000 rpm conditions which are much larger than 10000 suggesting a completely turbulence flow in both conditions [15]. The shear stress induced by the flowing electrolyte can be roughly evaluated based on the Re as 22 pa and 70 pa for the 1000 rpm and 2000 rpm conditions, respectively.

Four different fluid conditions were tested in this work: static 0.5 M NaCl solution; 0.5 M NaCl solution under rotating speed of 1000 rpm; 0.5 M NaCl solution under rotating speed of 2000 rpm; 0.5 M NaCl solution under rotating speed of 2000 rpm with 10% sand added (by weight, Bunnings Australia). Over 95% of the sand particles are composed by silica sand and the diameter of the sand particles were ranging from 240 μm to 380 μm (300 μm average diameter). The hardness of the sand particle was about 1200Hv and most of the sand particles presented a round shape (without sharp edges). In order to measure local currents over the electrode array surface, electrode terminals of the electrode array were connected to a custom-designed multiplexer enabling the measurement of current flowing into or out of each electrode in the electrode array. A Zero Resistance Ammeter (ZRA) was used to measure local current flowing to (or from) any electrode in the array by connecting the ZRA between the selected electrode and the remaining 99 electrodes (switching once every 10 s). The WBE current maps were obtained by mapping local currents over the WBE every 10 min, in the same way as that described previously in references [24,25].

After the completion of the tests, the rust layer on the coupon electrodes and the WBE surface was removed using a standard ASTM G1-03 rust removal solution and the surface images were taken by a digital camera. The surface of the WBE after each test was replicated using a Struers repliset-F5 kit for optical surface profilometry measurements of each wire in the array using an Alicona infinite focus microscope. The surface profilometry results were processed to calculate the negative volume of each wire (volume below the main plane).