Improvement Flow Accelerated Corrosion resistance of Carbon steel by Chromium electroplating and Plasma Nitriding

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1. Introduction

Flow-Accelerated Corrosion (FAC), which is chemical or electrochemical corrosion process by mass transfer [1] and Erosion-corrosion (EC), which is mechanical wear process [2] are forms of corrosion that takes place when water flows across the surface of carbon steel, causing the normally protective oxide layer to dissolve, which then lead to wall thinning and rupture in nuclear power plants such as PWR (Pressurized water reactor), CANDU (Canada deuterium reactor) and fossil power plants [3]. Furthermore, the pipes used in Small Modular Reactors (SMRs) being developed as an alternative to meet the increasing energy demand and environmental issues have smaller diameter and thickness compared to operating power plant, while their length is increased. As a result, SMRs is even more vulnerable to degradation problems such as FAC and EC.

The influential factors of FAC include material composition (Chromium content), environment (magnetite solubility, pH, temperature, oxygen content), and hydrodynamic parameters (mass transfer coefficient) [4]. Replacing materials can be expensive compared to the existing ones, and low-alloy with a Chromium content of 2.25 wt. % is vulnerable to erosion despite its excellent FAC resistance. Additionally, controlling the hydrodynamic parameters can lead to some susceptibility to corrosion depending on the operating variables. Therefore, this study aims to enhance pipe performance while maintaining the existing material by electro-plating Chromium, a functional material with corrosion and wear resistance, and plasma nitriding on the surface of carbon steel pipes. Prior to applying the plating to actual pipes, the optimal plating conditions were determined for the disk-shaped specimens, and FAC acceleration tests were conducted.

2. Methods and Results

2.1 Methods

The specimen (0.19 C, 0.25 Si, 0.98 Mn, 0.012 P, 0.004 S, 0.02 Cu, 0.04 Cr, 0.03 Ni, 0.01 Mo, 0.001 Ti, 0.008 Nb in wt. %) with diameter and width of 12 and 2 mm, respectively, was fabricated from SA-106 carbon steel. To achieve uniform deposition, the specimen surface was polished successively using 2400-grit SiC abrasive papers and 1 μm diamond suspension. The surface of the SA-106 carbon steel disk was coated with Chromium using an electroplating system and RF power plasma nitriding, as described in our previous publication [5]. The entire and half of the surface of specimen were coated with Chromium and plasma-nitrided at 50 ℃ and 70 ℃. To evaluate the FAC resistance, a FAC test system was designed and fabricated, as already described in previous publication [5]. FAC accelerated tests were conducted in aqueous environments of deionized water, 3.5 wt. % NaCl, and 3.5 wt. % NaCl + 1,000 ppm Al_2O_3 solutions at 25 ℃. After waiting for 30 minutes to allow NaCl and Al2O3 to fully dissolve in deionized water, the solution was stirred. FAC test were examined for 5 hours on fully and half coated carbon steel disk in three types of solution at a rotation speed of 2,000 rpm.

2.2 Results

The metal weight loss rate, ΔW, is a commonly used measurement to determine the corrosion rate of a metal. To convert this measurement to an average corrosion rate in millimeters per year [6]. Figure 1 shows the corrosion rates (mm / year) of carbon steel disk with Cr-coated and plasma nitrided by the FAC test in a 3.5 wt. % NaCl solution for 5 hours at 2000 rpm at room temperature. The carbon steel SA106 has been calculated to have a corrosion rate of 0.85 mm/yr. Cr-coated disk at 50 ℃ showed a corrosion rate of $0.25 \cdot 10^{-3}$ mm/yr, which is 3/100 times lower than the carbon steel and 70 ℃ Cr-coated disk did not show any weight loss. This results is believed to be due to the mechanism of Cr layer formation in electroplating. Figure 2 shows the SEM cross-sectional photographs of specimens electro-plated at 50 ℃ and 70 ℃. The two main factors that affect electroplating are current density and the temperature of the plating bath. The impact of current density and temperature on the coating layer has already been addressed in previous study. From a technical standpoint, the Cr-coated disk at 50 ℃ exhibit micro-crack, while those coated at 70℃ are free from crack. Similarly, in the case of half coating, the Cr-coated at 50 ℃ disk showed a higher corrosion rate than those coated at 70℃. And Figure 3 shows SEM images of the interface between the coated and the surface of the carbon steel disk after the FAC tests, and galvanic corrosion was not observed. The Cr-coated and nitrided disk increased corrosion rate compared to the fully Cr-coated disk at 50 ℃ and 70 ℃. In the 50 ℃ Cr-coated disk, the corrosion rate decreased compared to the half-coated, as the micro-cracks showed a recovery effect through nitriding. And the 70 ℃ Cr-coated disk showed more micro-crack in the Cr layer than before, as crack occurred during nitriding at 600 ℃ [7]. In order to investigate the effect of erosion-corrosion on FAC, the test was conducted by adding 1,000 ppm of alumina. The E-C tests with the added alumina and FAC test with 3.5 wt. % NaCl solution show similar trends. However, the difference in that galvanic corrosion was observed at the interface between coated and un-coated surface during the E-C test.

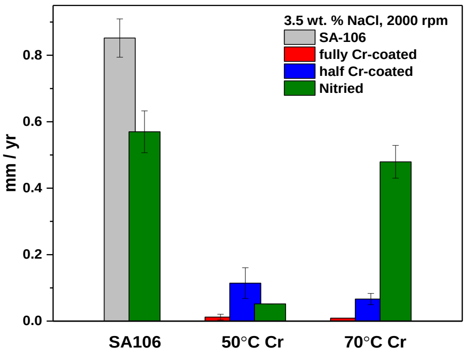
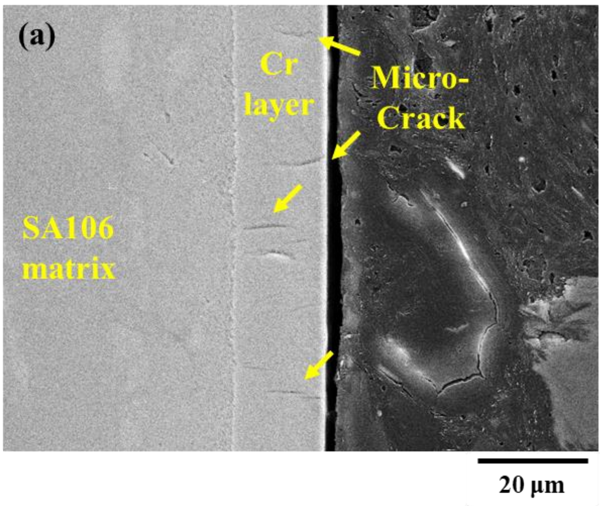


Fig. 1. Flow Accelerated Corrosion rate of as-received, Cr-coated, and nitrided SA106 disk calculated from FAC tests.



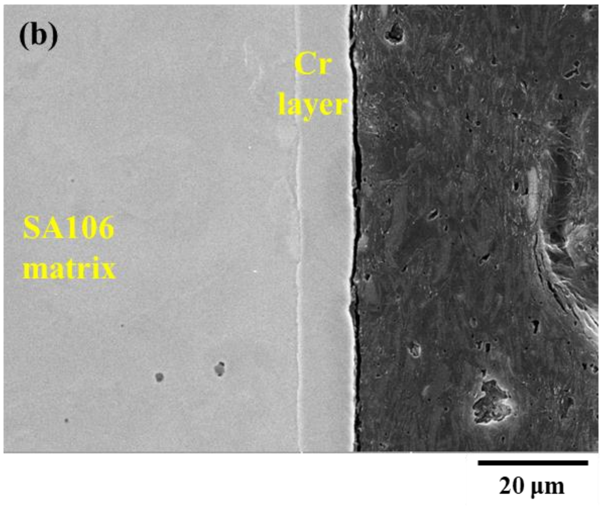


Fig. 2. The SEM cross-sectional photographs of Cr-electro-plated SA106 carbon steel at (a) 50 ℃ and (b) 70 ℃.

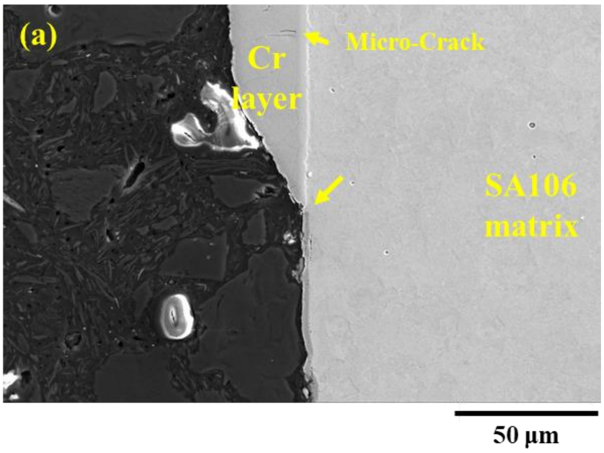


Fig. 3. The interface between Cr-coated at 50 ℃ and the carbon steel disk SEM photographs.

3. Conclusions

Chromium electroplating and RF power plasma nitriding are two technologies that can be utilized to enhance the flow accelerated corrosion and erosion-corrosion resistance of carbon steels. Under specific coating conditions, such as utilizing a direct current and a current density of 88 A/dm^2, the resulting thickness of the Cr layer is approximately 10 to 20 µm. In terms of corrosion resistance, the presence of micro-cracks in the coating layer is a more crucial factor than the thickness of the layer. A Cr layer with a crack free at room temperature exhibits excellent corrosion resistance. However, in operating conditions where temperatures exceed 150 ℃, crack may develop in the coating layer, resulting in a deterioration of its corrosion resistance. On the other hand, the 50 ℃ Cr-coated layer exhibits numerous micro-crack at room temperature. However, through the process of plasma nitriding, the cracks can be healed, resulting in an improvement in corrosion resistance.

In the future works, an analysis of single and composite coating layers will be conducted based on data obtained from harsher environments and actual simulation tests.

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