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Performance testing of nickel and palladium coatings for venturi fouling mitigation

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1. Introduction

In nuclear power plants, the thermal power is calculated using the thermal balance equation based on the main feedwater flow rate supplied to the steam generator. The main feedwater flow rate is measured through a venturi flowmeter installed in the main feedwater pipe of the secondary system. However, the venturi flowmeter has a fouling issue. Fouling is a phenomenon in which microparticle suspension such as iron oxide (Fe_3O_4, magnetite) are deposited on pipe walls and near venture holes, thereby changing surface roughness, and causes an error in the measurements of the venturi flowmeter.

Because of the fouling in Korean nuclear power plants, the pressure loss value of the flow rate has increased by 0.3 % every year, which has led to the problem of reducing the power generation of nuclear reactors [1,2]. In addition, economic losses are incurred due to the cleaning or replacement of the venturi flowmeter during the regular planned preventive maintenance [1].

Up to this time, the domestic studies on the venturi fouling have such a limitation that only structural modification of the venture design or changing operation methods have been performed [2,3]. It has been reported that General Electric company in the United States solved the fouling phenomenon in the jet pump pipe of the boiling water reactor (BWR) by applying a TiO_2 coating technology [4].

Therefore, we used electroless nickel (Ni) and palladium (Pd) plating on stainless steel used as venturi material and evaluated their corrosion resistance using a static autoclave. Furthermore, the differential pressure was measured using a coated mock-up venture flowmeter in a simulated secondary feedwater condition. Suggested coatings in this study can be applied to reduce the deposition of iron oxide inside the venturi system and minimize the error in the main feedwater flow rate measurement.

2. Experimental Procedures

2.1 Specimen preparation

The specimens used in this study were commercial 304L stainless-steel with 10 mm x 25 mm x 2 mm. The chemical composition of them is shown in Table I. All surfaces of each specimen were mechanically polished with silicon-carbide papers up to 800 Grit, and then ultrasonically cleaned in ethanol and deionized water and dried. Electroless Ni and Pd plating were conducted onto polished specimens.

Table I: Chemical composition of Test Material (wt.%)

C	Si	Mn	P	S
0.0237	0.366	1.439	0.0298	0.0032
Cr	Ni	Cu	Mo	Fe
18.261	8.098	0.251	0.081	Bal.

2.2 Static corrosion test

The experiments were conducted in a static autoclave operating in the simulated secondary water chemistry condition at 235℃ and 27 bar. Figure 1 shows the static autoclave system. The pH=9.3 of the simulated secondary water condition was adjusted with ethanolamine, and 60 ppb hydrazine was added to the solution. Also, carbon steel pieces were placed inside the autoclave to simulate iron (Fe) injection. The pieces were divided into 4 parts of carbon steel with a diameter of 25 mm and a thickness of 2 mm. The solution was deaerated using argon gas for the initial 6 hours and maintained at 130 ℃ for 2 days to sufficiently dissolve Fe in the test solution. Then, the temperature was raised to 235℃, and experiment was conducted for 4 months.

The immersed specimens were retrieved and ultrasonically cleaned to remove the contamination, and mass changes were measured. Extensive microstructure characterization was also conducted using field emission scanning electron microscopy (FE-SEM, Mira3, Tescan) at 15 kV, while the chemical composition was evaluated using an energy dispersive X-ray spectroscopy (EDS, X-max, Oxford). The crystal structures were analyzed by X-ray diffraction (XRD, Ultima IV, Rigaku) using Cu-Kα radiation at 40 kV/20 mA. The diffraction patterns were scanned at 20–80° with a 0.02°/s.

Fig. 1. Static autoclave corrosion test apparatus.

2.3 Venturi performance test

Figure 2 shows the venturi performance test system, which consists of water chemistry simulation system for the secondary water chemistry conditions (pH, pressure, temperature, impurity, etc.), venturi fouling test section, and test control and measurement system. A total of three mock-up venturi flowmeters were installed in the test section, and a differential pressure gauge for real-time measurement was installed. The differential pressure gauge (3051D model, Rosemount) used in the test has a measurable range of 0 to 1.5 bar. Also, a circulation pump was installed to control the flow rate of 5 m/s in the mock-up venturi pipe. To accelerate the fouling phenomenon, Fe as iron nitrite was additionally injected with the concentration of 5 ppm, which is 1000 times higher than the iron concentration limit (5ppb) of the secondary water chemistry condition. Hydrazine was not added. The temperature and pressure were maintained at 150°C and 40 bar, respectively, and the performance testing was conducted for about 10 days. For smooth injection, ETA and iron nitrite were dissolved in deionized water and injected in the form of an aqueous solution using a chemical injection pump.

Electroless Pd and Ni plating was conducted on the inside and outside of the mock-up venturi, as shown in Fig. 3. Each coated venturi was tested for the performance in simulated environments with an uncoated mock-up venturi. Differential pressure data measured from each venturi can indicate whether the fouling occurs or not. The surface and cross-section analysis for each venturi were conducted using FE-SEM.

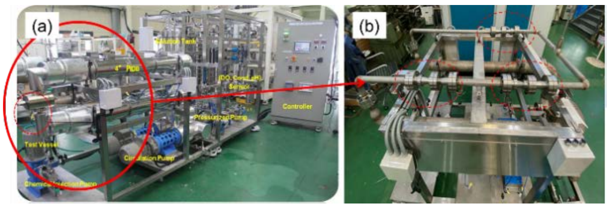

Fig. 2. (a) Simulated venturi performance test system. (b) venturi fouling test section.

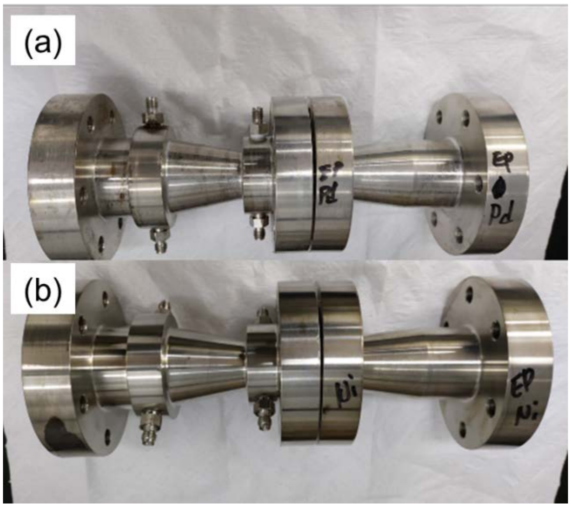

Fig. 3. The mock-up venturi for the performance test: (a) the Pd-coated, (b) the Ni-coated.

3. Results and Discussion

3.1 Static corrosion test

The measured mass change after the ultrasonic cleaning is given in Fig. 4 as a function of time. The increase in the mass of the specimen implies that an oxide film forms or iron oxide particles deposit on the surface. The mass loss can be observed due to oxide spalling or metal dissolution. Ni-coated specimens show mass loss, whereas Pd-coated specimens show mass gain. Furthermore, as the corrosion test period increases, the mass change rate gradually decreases for the Pd-coated specimens but increases for the Ni-coated specimens.

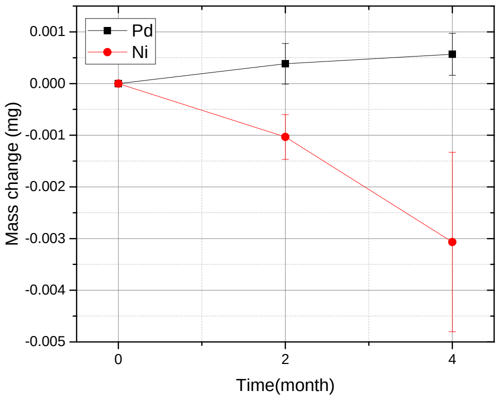

Fig. 4. Mass change of the coated specimens after the static autoclave corrosion test.

SEM images of the specimen after the static autoclave corrosion test are given in Fig. 5. The initial surface of the specimen plated by Ni (Fig. 5a) was very smooth. However, after the corrosion tests for 2 and 4 months, the surface morphology (Fig. 5b, c) indicated the metal dissolution. This surface morphology change is considered as the main cause of the mass loss. According to EDS mapping results, uniform NiO layer is observable. This is consistent with the XRD results shown in Fig. 6.

Moreover, the XRD diffraction patterns provide that $Ni(OH)_2$ is present as well as NiO.

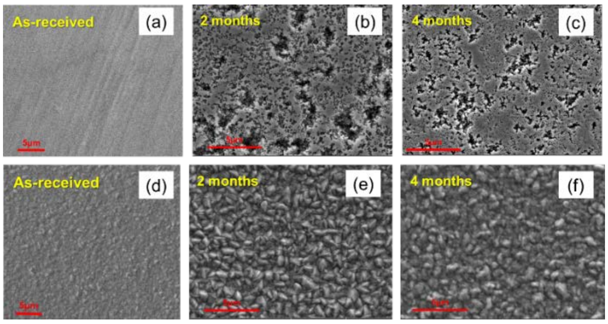

Fig. 5. SEM images for the surface of specimens with the different static corrosion test time: (a, b, c) the Ni-coated (d, e, f), the Pd-coated.

The specimen plated by Pd (Fig. 5d) reveal the initial homogeneous surface without porous structures or cracks, indicating the good quality of coating. Even after the 4-month exposure testing, the morphology of the surface (Fig. 5e, f) maintained the initial state. This proves that Pd is a noble metal so that the surface oxidation or dissolution is minimized. XRD results also support surface analysis results. As shown in Fig. 7, PdO was not observed on the 2-month exposure specimen, but after 4 months of static corrosion test, the presence of PdO on the surface was identified. The overall static corrosion test results indicate that corrosion resistance of Pd is superior to that of Ni in the secondary water chemistry condition of the nuclear power plant.

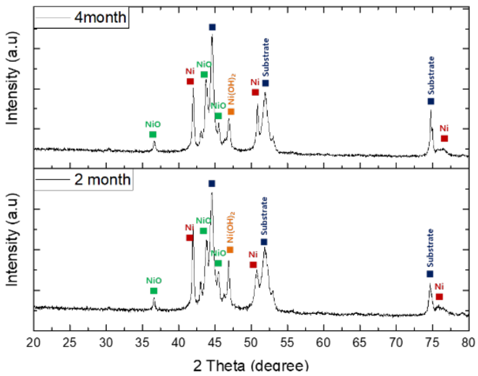

Fig. 6. XRD diffraction patterns of the specimens deposited by Ni with the different static corrosion test time.

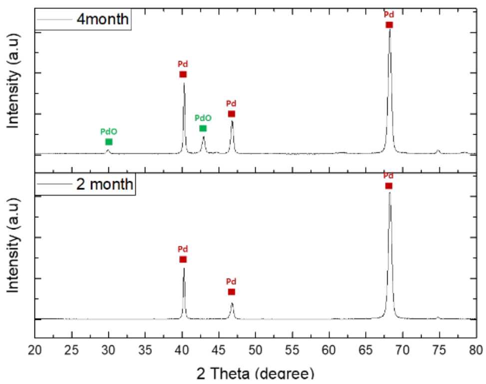

Fig. 7. XRD diffraction patterns of the specimens deposited by Pd with the different static corrosion test time.

3.2 Venturi performance test

The coated venturi showed less differential pressure change than the uncoated venturi, implying that the electroless Pd and Ni plating is effective to mitigate fouling. In particular, the Pd-coated venturi has a smaller fluctuation in the differential pressure than the Ni-coated one.

Figure 8a shows the cross-section of the pressure tap hole, and Figs. 8b~d show SEM images for the surface near the hole after the mock-up venturi performance test. On the surface of the uncoated venturi, oxide particles were observed, implying that fouling occurred on the uncoated stainless steel surface, as observed in the actual venturi surface of nuclear power plants. The Ni-coated venturi showed small pores, implying that Ni dissolution occurred on the surface. However, unlike the previous two cases, the Pd-coated venturi has a smooth surface without cracks or defects. Also, iron particles such as Fe_3O_4 were not observed. This is consistent with the results of the static corrosion test, suggesting that Pd can be a promising coating material to mitigate the fouling.

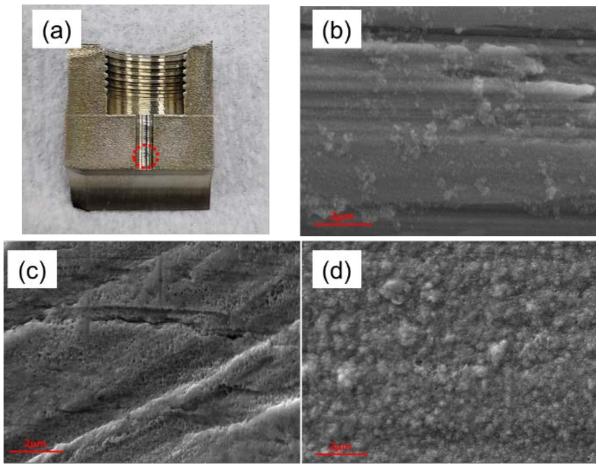

Fig. 8. (a) Cross section of the venturi hole, SEM images for the surface of specimens after the simulated venturi performance test: (b) the uncoated, (c) the Ni-coated, (d) the Pd-coated.

4. Summary & Conclusions

Electroless Pd and Ni plating was explored as one of methods to mitigate the fouling phenomenon occurring at the venturi flowmeter. Electroless Ni and Pd plating was conducted on stainless steel specimens, and their corrosion resistance was evaluated by static corrosion testing for max. 4 months. Furthermore, the differential pressure was measured using Pd and Ni-plated mock-up venturis installed in a test loop simulating secondary feedwater conditions. The main findings can be summarized as follows:

- Pd-coated specimens showed a small amount of mass gain, whereas Ni-coated specimens showed a large mass loss because of metal dissolution. The corrosion resistance of Pd was superior to that of Ni in simulated secondary water chemistry conditions.
- Uncoated venturi showed a relatively higher fluctuation in the differential pressure measurement and the oxide particle deposition on the pressure tap hole. Coated venturis showed relatively smaller fluctuations in the differential pressure, but Pd-coated one showed more stable values. Pd-coated surface on the pressure tap hole showed no indication of particle deposition or dissolution.
- Based on the static corrosion testing and mock-up venture performance testing, it is thought that Pd coating can be applied to mitigate the fouling at the venture flow meter.

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