Coating Techniques for Venturi Fouling Mitigation at Feedwater Pipe in Nuclear Power Plant Secondary System

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1. Introduction

In nuclear power plants, the thermal power of reactor is calculated by 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.

Due to the scale caused by fouling in Korean nuclear power plants, the pressure loss value of the flow rate has increased by 1 % to up to 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 through the cleaning or replacement of the venturi flowmeter during the regular planned preventive maintenance [1].

Up to this time, the studies on venturi fouling conducted in Korea have a limitation in that only methodologies that try to solve problems by structurally modifying the design of venturi itself or changing operation methods have been performed [2,3]. It has been reported that General Electric company (GE) 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, in this study, we apply various metal surface coating technologies such as physical vapor deposition (PVD) and electroless plating, so as to reduce the deposition of iron oxide inside the venturi system, to increase the operating time of the venturi, and to minimize the error in main feedwater flow rate measurement.

2. Experimental Procedures

2.1 Specimen Preparation

The specimens used in this study were commercial stainless steel (Type 316L, 304) and carbon steel (SA516-Gr.60) with 10 mm x 15 mm x 2 mm. All surfaces of each specimen were mechanically ground with silicon-carbide papers up to 600 Grit, and then ultrasonically cleaned in ethanol and deionized water for 10 min and dried.

2.2 Applied Coating Methods

In a broad sense, two techniques of coating were used. First, CrN, TiN, and Ti were deposited by PVD coating technology. Second, the Ni and Pd were deposited onto specimens using an electroless plating method. Coating was conducted by companies (Hyosin in Cheonan, J-tech in Incheon) who carry coating as an industry scale.

2.3 Coating Characterization

After deposited using various coating methods, the surface and cross-section of specimens were observed by 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 coating 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.

3. Results and Discussion

3.1 Surface Morphology of Coatings

Fig. 1 shows the SEM surface morphology of specimens deposited by PVD-CrN. Most defects can appear during deposition process [5]. The origin is microparticles that flake during heating, etching and deposition from coated components of vacuum system and incorporate in the growing coating [6]. The microdroplet shown in Fig. 1 is an example, and its size is less than about 2 μm. In addition, the pinhole, a trace of the microdroplet where it fell off, is also identified.

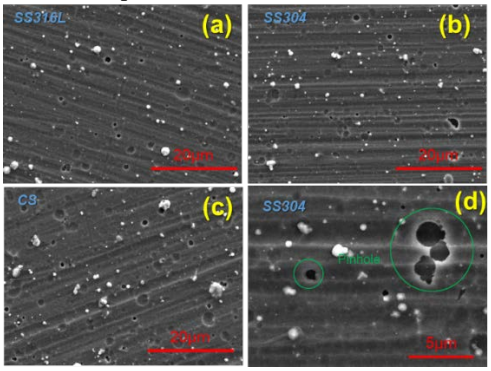

Fig. 1. SEM surface morphology of PVD-CrN coatings on (a) SUS316L, (b) SUS304, (c) CS, (d) SUS304-magnified.

Since these surface defects cannot be completely removed, it is necessary to remove the dust in the chamber and other components must be cleaned by blasting.

Fig. 2 shows the SEM surface morphology of specimens deposited by PVD-Ti and PVD-TiN. The surfaces showed no defects, and in the Ti coating layer, a puffy shape appeared. In TiN coating layer, a wavy shape appeared.

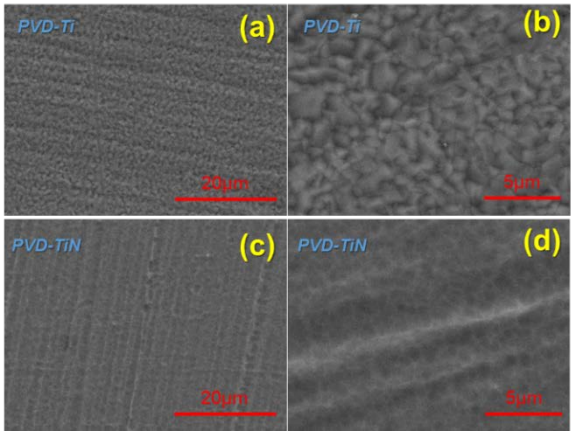

Fig. 2. SEM surface morphology of (a,b) PVD-Ti coatings on CS and (c,d) PVD-TiN coatings on CS.

Fig. 3 shows the surface deposited by electroless Ni plating. Unlike stainless steel, the surface of carbon steel has a local swelling shape, which seems to be attributed to insufficient surface polishing during the pre-treatment of carbon steel. Additional Ni plating experiments will be planned for further analysis.

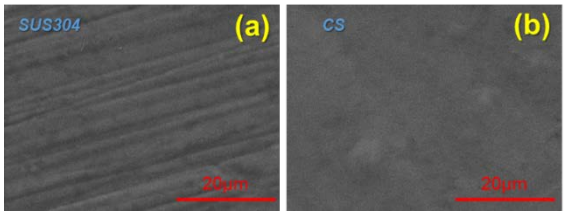

Fig. 3. SEM surface morphology of Ni electroless plating on (a) SUS304, (b) CS

Fig. 4 shows the surface deposited by electroless Pd plating. Cracks are visible on the surface regardless of base materials. The cross-sectional SEM analysis results revealed that the Pd coating was deposited as a double layer with Ni. These cracks are assumed to be caused by the Ni inner layer under the Pd layer. To remove the cracking issue, additional Pd plating without the Ni inner layer is also planned.

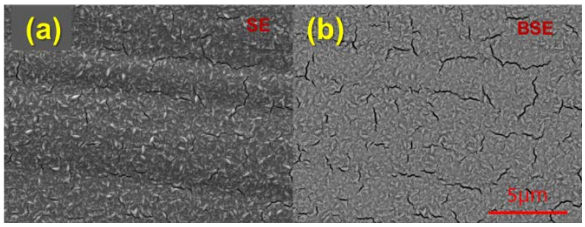

Fig. 4. SEM surface morphology of Pd electroless plating on SUS316L (a) SE mode, (b) BSE mode.

3.2 Cross-sectional Images of Coatings

To identify thickness and density of coating layer, cross-section of specimens was observed by SEM-EDS. In the case of Ti coating, since a small amount of nitrogen was detected, it is predicted that coating was contaminated by nitrogen already existing in the coating chamber. In the case of the Pd plating, double coating layer was identified which consisted of Pd as the out layer and Ni as the inner layer. The double layer seems to be a typical industry practice for Pd plating, but further discussion is necessary with the company on any procedure modification to achieve Pd only plating layer.

The thickness of coating layer is shown in Fig. 5. CrN coating layer was the thickest. The Pd coating layer was very thin when excluding the 4~5 μm Ni inner layer. Since the thickness of the coating layer can be adjusted by temperature, deposition time, voltage, etc. during the process, it is expected that the target coating layer thickness of 2 to 3 μm required for a venturi flowmeter is achievable.

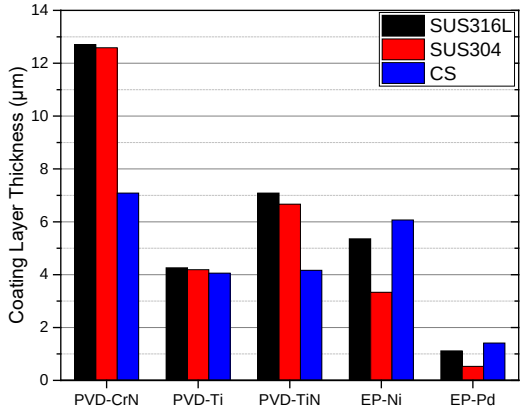

Fig. 5. The thickness of coating layer.

3.3 Crystal Structure of Coatings

XRD results obtained for the coated SUS304 specimens are presented in Fig. 6. ‘x’ mark in the graph means peaks of the base metal. The diffraction peaks for the specimen PVD coatings were identified with the CrN and Cr_2N peak. This result is not unexpected because CrN as well as Cr_2N can be formed depending on the temperature in the vacuum chamber during the coating process [7]. The diffraction peaks for the Ti coatings were identified with mainly Ti peak and tiny TiN peak. Also, the diffraction peaks for the specimen deposited by

Pd using electroless plating were identified with the Pd as well as the Ni. As discussed before, these results were consistent with the cross-sectional image analysis showing the double layer.

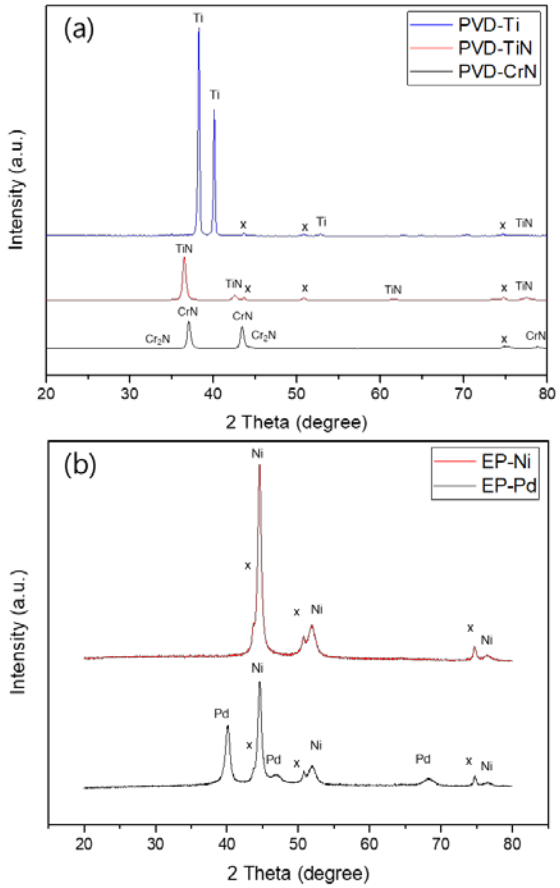

Fig. 6. XRD patterns of SUS304 specimens deposited by (a) PVD and (b) electroless plating.

4. Conclusions and Future Work

In this study, various coatings were deposited on stainless steels and carbon steels and characterized by SEM-EDS and XRD.

As a result, the TiN coating by PVD, which showed no defects on the surface and a dense coating layer, is considered as the best option so far. However, since surface defects such as pinholes and microdroplets on CrN coating by PVD can be sufficiently removed during the process, further coating experiments and analysis are required to select the optimal coating.

It also plans to conduct performance tests (such as corrosion of coating layer, adhesion test, etc.) on coated specimens in the same water chemistry environment as the nuclear powerplant secondary system.

The final goal of this study is to determine a coating material and methodology that enables to mitigate the venturi fouling, and to produce a prototype of a venture flow meter that can be used in the field to which the coating is applied.

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