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Ni Plating Technology for PWR Reactor Vessel Cladding Repair

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SA508 low-alloy steel for a reactor vessel was exposed to primary water in a pressurized water reactor (PWR) plant because the cladding layer of type 309 stainless steel for the RPV was removed, due to an accident in which the detachment of the thermal sleeve occurred. The major advantage of the electrochemical deposition (ECD) Ni plating technique is that the reactor pressure vessel can be repaired without significant thermal effects, and Ni has solid corrosion resistance that can withstand boric acid. The corrosion rate assessment of the damaged part was performed, and its trend was analyzed. Essential variables of the Ni plating for repair of the damaged part were derived. These conditions are applicable variables for the repair plating device, and have been carefully adjusted using the repair plating device. The process for establishing ASME technical standards called Code Case N-840 is described. The process of developing Ni-plating devices, and the electroplating procedure specification (EPS) are described.

Keywords: *ASME code, PWR, Low-alloy steel, Stainless steel cladding, Ni plating*

1. Introduction

SA508 low-alloy steel for a reactor vessel was exposed to primary water in a pressurized water reactor (PWR) plant because the cladding layer of type 309 stainless steel for the RPV was peeled off due to an accident in which detachment of the thermal sleeve occurred. SA508 low-alloy steel is susceptible to general corrosion when exposed to primary water during the refueling time of relatively high oxygen concentration. It is a potential threat to the integrity of the reactor pressure vessel (RPV). Repair of the interior of the reactor vessel is challenging because of high radiation levels and underwater conditions. Welding, a common repair technique, requires heat treatment because it has high heat input and causes residual stress due to deformation. On the other hand, the advantage of the electrochemical deposition (ECD) Ni plating technique is that it has no significant thermal effects, and Ni has good corrosion resistance in primary water. In addition, its adhesion strength has been verified by previous results [1,2]. The ECD process was previously approved by the ASME for repairing the surfaces of steam generator tubes in terms of the ECD technology as ASME Code Case N-569 [3]. Another newly proposed code case is based largely on the groundwork of the code case N-569. The ECD technology used to repair the cladding was also approved as the ASME code case N-840 (CC N-840) in 2013 [4]. The purposes of this article are to review the corrosion trend of the damaged area, to review the code requirements, to create standard conditions for sound Ni plating in an RPV, and to develop a plating system based on the ASME code case N-840. The corrosion rate of the SA 508 low-alloy steel of the plant was about 0.1 mm/year. The standard plating conditions were developed in terms of pH adjustment, as well as the evaluation of Ni anode materials, the strike layer formation process, plating temperature, and current density.

2. Experimental Methods

The first step was to evaluate the damage of the cladding. Then the corrosion rate trend on the damaged area was documented for 16 years. Development history of Ni plating variables was reviewed, and preliminary conditions were based on a long-term research project [1]. The ASME standard development process is described herein. As the main part of this work, a Ni electroplating system design and manufacturing process are described. After the plating procedure using this equipment was verified, a preliminary EPS was developed.

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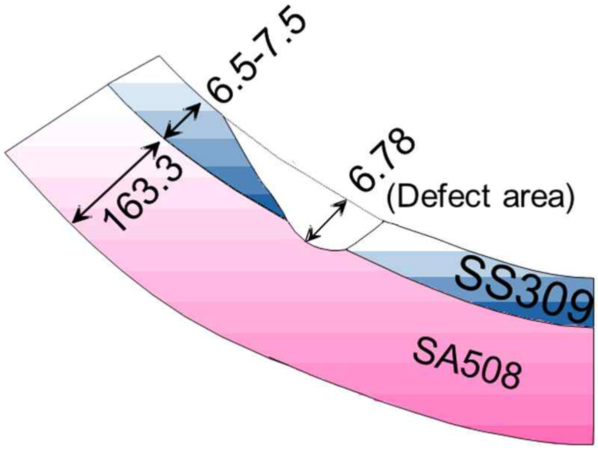

Fig. 1 Schematic of the cladding damage.

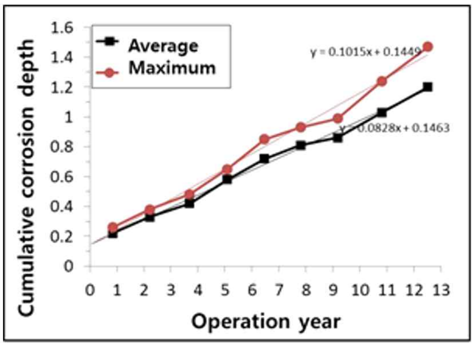

Fig. 2 Corrosion rate of the damaged area.

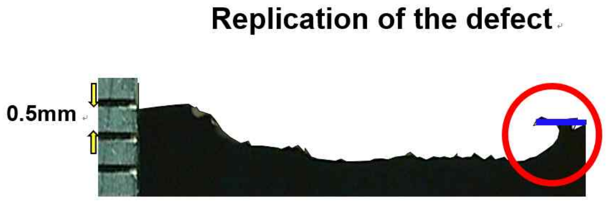

Fig. 3 Corrosion trend of depth and lateral directions.

3. Results and Discussion

3.1 Evaluation of damage of the cladding

Because of the detachment of the thermal sleeve from the primary coolant nozzle in a PWR plant, the stainless steel cladding at the bottom of the reactor vessel was damaged due to the vibration of the thermal sleeve. The base metal of the SA 508 reactor vessel steel had been exposed to the primary coolant for over 16 years after the accident, as shown in Fig. 1.

3.2 Corrosion trend of the vessel metal

The corrosion trend on the damaged area was monitored by using the replication method for 16 years. As shown in Fig. 2, the average corrosion depth of the flaw was 0.0828 mm/year.

It was confirmed that the corrosion progress was within the predictable range through the accumulated experimental results. As of April 1, 2017, the date of taking the 11th replication sampling analysis, the maximum cumulative corrosion depth considering the cumulative corrosion depth of 1.724 mm and the additional margin of 0.5 mm after 5 years was estimated to be 2.482 mm. Therefore, the predicted maximum cumulative corrosion depth after 5 years is only 4.15% of the 58 mm, which is the thickness that ensures the structural integrity of the pressure vessel. As a result of measuring the lateral direction corrosion depth based on the position of the 11th replication sampling analysis, the average corrosion depth was 0.81 mm, and the maximum corrosion depth was 1.27 mm. It was also observed that the width of the flaw gradually increased due to the progress of lateral corrosion, as shown in Fig. 3.

3.3 Development of Ni plating variables

The corrosion depth of 6.78 mm seems to be much thinner than the tolerance of 59.8 mm thick for the reactor vessel considering the operation of the reactor for 60 years. It is necessary to restore the damaged area to the original condition to secure the soundness of the plant. This can reduce the burden of inspection every cycle and help to improve the soundness of the plant.

Detail results for supporting the code case were described in PVP2013-97857 [2,5]. The code case was proposed as an alternative method for cladding repair by ECD. It is especially useful for applications in damaged regions where access is limited in underwater conditions. Determining the optimum condition of ECD layer formation is very important for the integrity of the deposit. Factors of electro-deposition for the optimum conditions were the current density, temperature, solution composition, and pH. In addition, qualification tests of the ECD layer are needed to verify the integrity of the ECD layer. One of the validation processes is a side-bend test, which indicates the adhesion strength of the ECD layer and strike layer.

As shown in Fig. 4, the optimum thickness condition of the strike layer was 5 μm, and there was no bulging or detachment at the surface.

The tensile strength of the ECD layer using the SS309 substrate was measured to be 94.8 MPa or more, as shown in Fig. 5. Due to this strength, the deposit layer adhered to the SS309 substrate after the tensile test. The measured bond strength was considered suitable for the proper integrity of the ECD for plant operation or service conditions.

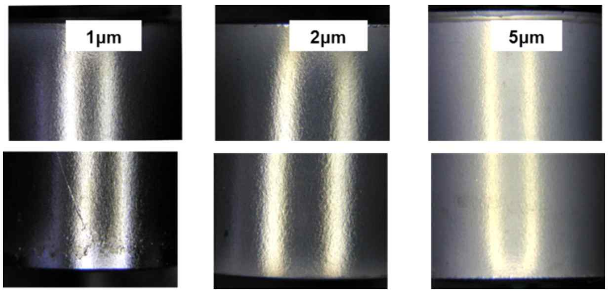

Fig. 4 Feature of strike layer with various thicknesses.

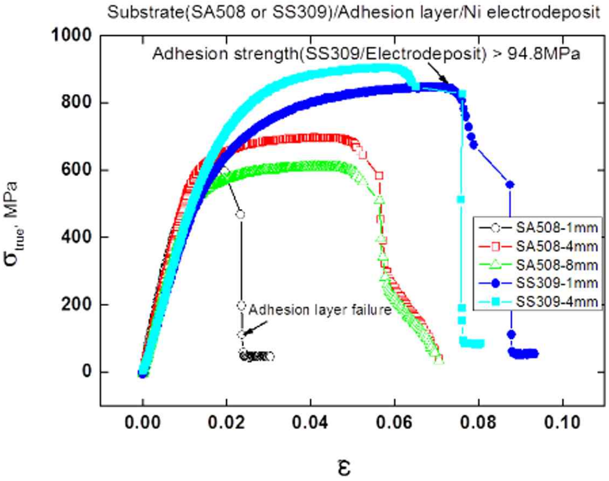

Fig. 5 Stress-strain curves with various adhesion areas.

As another qualification test, side-bend testing was performed in accordance with ASTM procedures E290 and B489 to verify the ductility and adhesion, and the results were described in the reference [1]. After bending, deposits were visually inspected for defects. Bond failure did not occur in any qualification specimen, according to observations under a 10X magnifier; thus, the ductility of the ECD deposits was determined to be acceptable. The guided-bend test (side-bend test) in the ASME section IX, QW-160 [5], was performed to evaluate the adhesion of the ECD deposit on the substrate. The side bend specimens were prepared on two different substrate materials, SS309 and SA508, with a 5-μm strike layer. After the formation of the ECD deposit, the specimens were bent with a side-bend test jig based on the ASME section IX, QW-466.1, as shown in Fig. 6 [5].

Fig. 7 shows the boundary layer between the ECD layer and the substrate after the side-bend test. The ECD layer was firmly adhered, and there was no detachment at the interface, regardless of the SA 508 or type 309 SS materials. Therefore, the bonding integrity of the strike layer was verified from the bend test.

It is also necessary to develop a practical Ni plating system that can allow the operator to control the deposition variables remotely in a high-radiation operating reactor condition. The plant utility launched a new research project that includes all steps from setting up the electro-deposition variables to resolving the regulatory issues with a plan to repair damaged areas, as shown in Fig. 8.

3.4 ASME standard development

Because there was no adequate repair procedure in Korea Electric Power Industry Code (KEPIC) MI and ASME section XI, a process to develop a new code case in the ASME committees was suggested in 2010 based on a previously developed Ni electroplating technique.

The first step to initiate code development was to raise an inquiry regarding whether there was an adequate repair procedure in ASME section XI. The committee recommended the staff secretary to send us the following response: 'ASME Section XI does not address this issue, but has initiated an action to address underwater cladding repair' in November 2010.

The second step was to set up a task group in which technical details were discussed. Some members from the working repair and replacement activities volunteered to join the task group called 'Underwater clad repair by Ni Plating' in February 2011, and the technical discussion

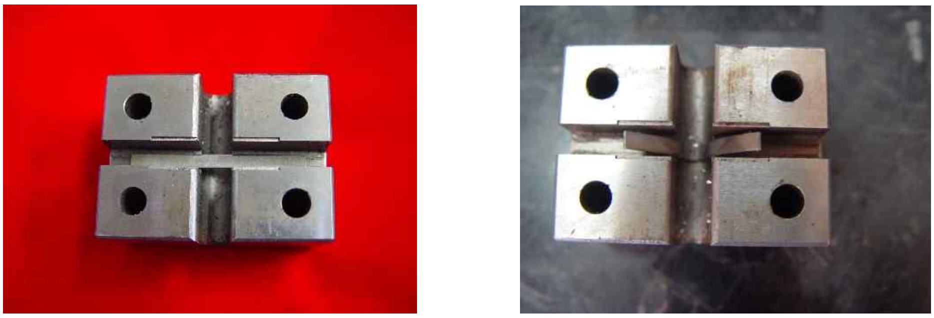

Fig. 6 Side bend test jigs and a bent sample in the jig.

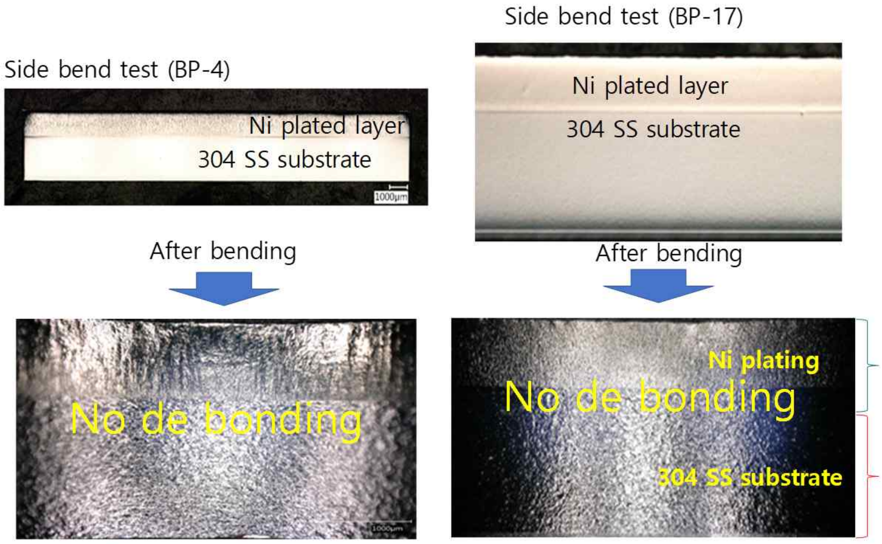

Fig. 7 Boundary layer between the ECD layer and the substrate after the side-bend test.

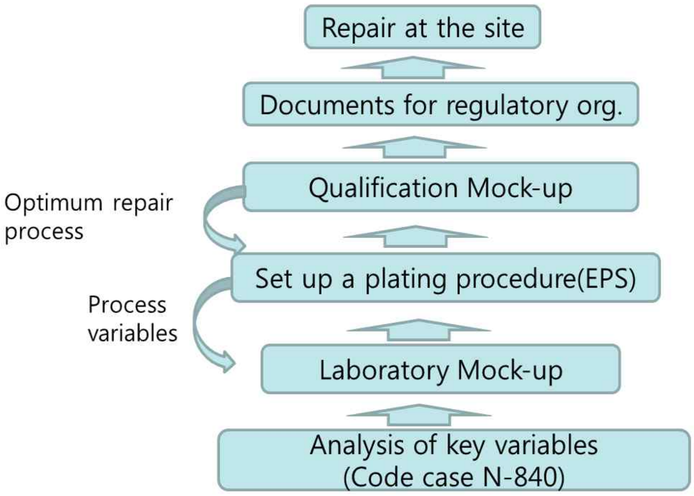

Fig. 8 General scheme of the project for field application.

group continued for two years until October 2013 when the section XI standards committee finally approved the code case called ‘Case N-840 Cladding Repair by Underwater Electrochemical Deposition in Class 1 and 2 Applications Section XI, Division 1’[5].

3.5 Ni plating system design

Fig. 9 shows the Ni plating system, which allows the Ni plating solution to be transported sequentially, including the pretreatment solution. This system was designed to be used underwater. The four magnetic pumps quickly transfer the pretreatment solutions to induce degreasing, activation, and strike layer formation on the specimen. Since Ni plating should be performed at around 60 °C, the plating bath is equipped with a heater. It is also equipped with a stirrer to stir the plating solution of 1.39 mol/l of Ni sulfamate and 0.65 mol/l of boric acid.

Fig. 9 also shows the plating chamber connected to the sequential plating bath. The plating chamber induces an actual plating reaction on a 400 × 400 mm^2 flat specimen for demonstration at the moment. The schematic drawing of the plating apparatus is shown in Fig. 10.

3.6 Development of EPS

The plating apparatus should be remotely controllable to repair the nuclear reactor under a highly radioactive environment. After verification of the plating procedure using this device, a preliminary EPS, which is document

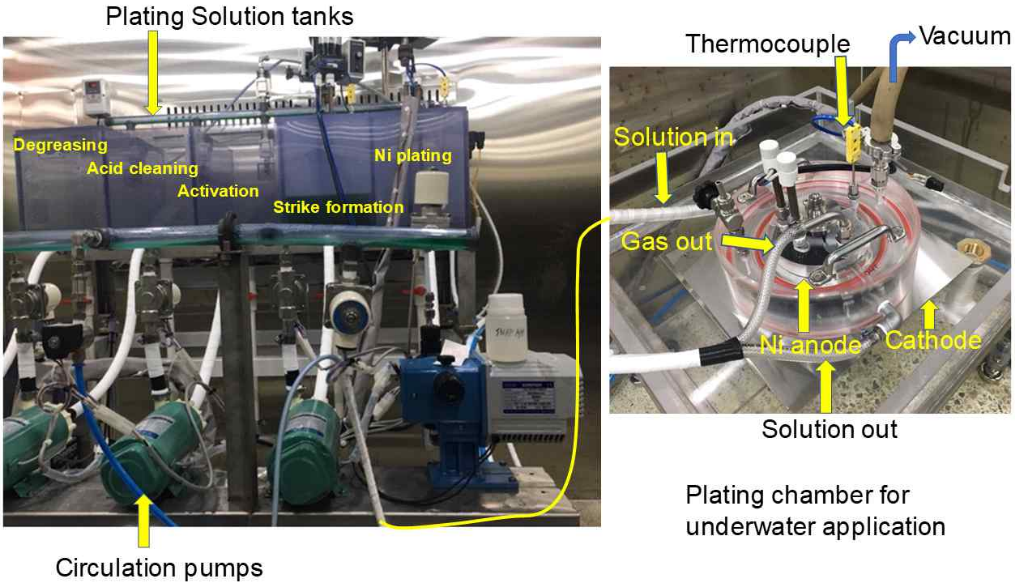

Fig. 9 Plating solution supply system and Ni plating chamber.

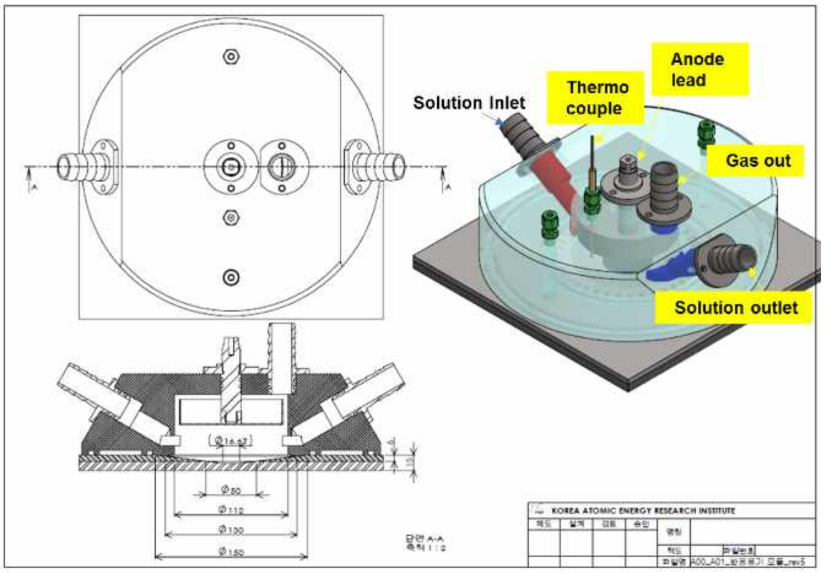

Fig. 10 Schematic diagram of Ni plating system and details of the Ni plating chamber.

of the nature of the welding procedure specification (WPS) applied at welding, was developed.

All the processes, except for filling the plating solution into the plating bath, were operated by touching through the control panel. The purpose of the test procedure development is to ensure that the person who first accesses the device can do this while watching the control panel. Since the plating conditions are limited by temperature, pH, current density, plating time, and so on, it is easy to follow the procedure step by step.

4. Conclusions

- SA508 low-alloy steel for a reactor vessel was exposed to primary water in a pressurized water reactor (PWR) plant due to an accident to the detachment of the thermal sleeve.
- The corrosion rate of the SA 508 low alloy steel of the plant was about 0.1 mm/year.
- Ni plating variables were developed for the field application, and the standard procedure of the process

(electrodeposition procedure specification (EPS)) was developed

- The ECD layer was firmly adhered, and there was no detachment at the interface, regardless of the SA 508 or type 309 SS materials.

Acknowledgments

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