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Repair technology by Ni electrodeposition for RPV cladding

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1. Introduction

Carbon/low alloy steel is susceptible to general corrosion when it is exposed to primary water of PWR(Pressurized Water Reactor), especially during refueling time, which is a potential threat against the integrity of the RPV(Reactor Pressure Vessel). The SA508 low alloy steel was exposed to primary water in a PWR plant because the cladding layer of type 309 stainless steel was peeled off due to an accident with the detachment of the thermal sleeve.

Based on the extensive research [1, 2] conducted by KAERI, the US ASME standard (code case N-840), which is a nuclear pressure vessel construction and in service inspection standard, has been developed [3]. This technology is based on the Ni plating method and has no thermal effect on the material as compared with general welding repair, and has technical merits such as excellent corrosion resistance in the operation condition in PWR primary cooling water.

Plating experiments on Type 304 stainless steel resulted in the formation of a good 1 mm thick plating layer and the detailed plating conditions were obtained. In the side bend test, the plating layer showed firm adhesion properties without peeling, and the results of the chemical composition analysis showed good contents of each component according to the standard.

In this paper, the results of an empirical test for the repair of cladding layer using Ni plating method are described.

2. Experimental

2.1 Specimen

A type 304 stainless steel plate of 300 mm, 300 mm, and 2 mm in width, length, and thickness was used for plated specimens which had been subjected to clad damage, and the chemical composition of the specimen plate is shown in Table 1.

Table 1 Chemical composition of the test specimen

Element	C	Si	Mn	P	Fe
Wt%	0.0537	0.390	1.126	0.0328	Rem.
Element	S	Cr	Ni	N(ppm)	
Wt%	0.0042	18.228	8.057	332	

2.2 Ni plating procedure

The plating test procedure is briefly described in Fig. 1. Degreasing and activating the surface to be plated and then forming a strike layer and then performing the main plating process. Experiments were conducted to fabricate a plating layer by flowing solution into the plating chamber, which is designed and manufactured by the research team. The schematic drawing of the plating apparatus is shown in Fig. 2.

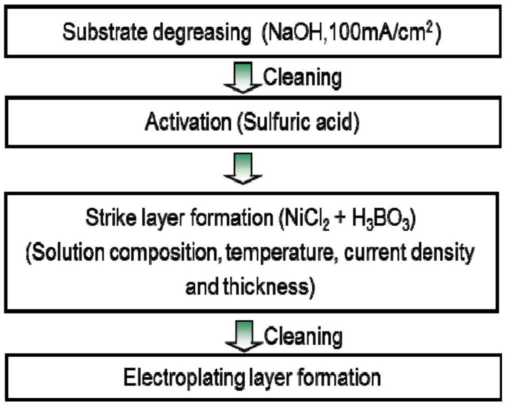


Fig. 1. Flow chart of plating process

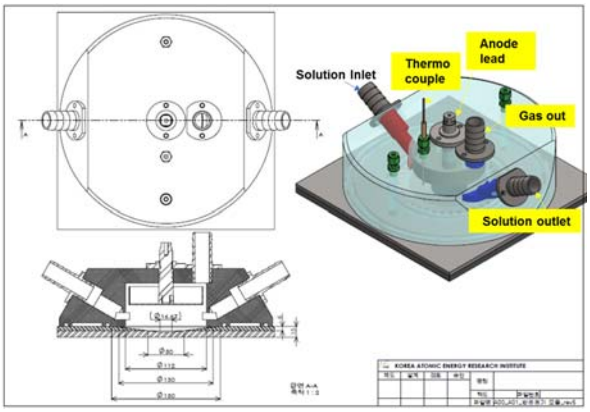


Fig. 2. Ni plating chamber system

2.3 Integrity evaluation

The main chemical compositions of the plating layer were analyzed by ICP MS (Inductively Coupled Plasma Mass Spectrometry) according to KS D 2598 method.

Side bend tests were performed according to the ASME section IX, QW-160 (GUIDED-BEND TESTS) [4]. If the width (W) is less than 10 mm, the fixture is manufactured according to ASTM E 290 [5] as an alternative to QW-462.2 as shown in Fig. 3.

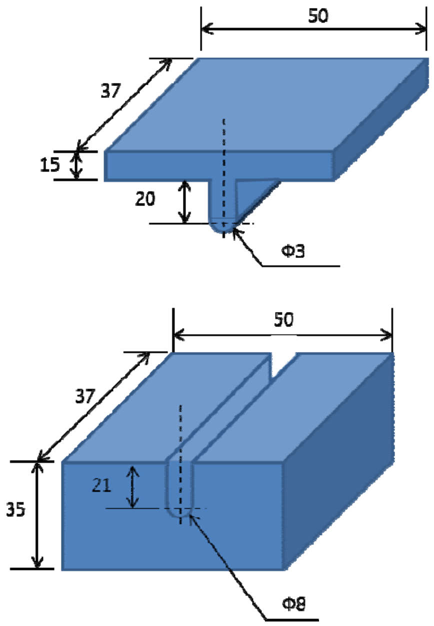


Fig. 3. Schematic of the side bend test jig

The wear corrosion rate of Ni metal was evaluated using published data [6].

3. Result and discussion

3.1 Ni electrodeposition result

The result of plating on 304 stainless plate is shown in Fig. 4. Experiments were carried out in a chamber designed considering the slope of the damaged part of the reactor, and the results were obtained by plating for 10~30 hours at 60 ℃and 5 A/dm^2. The thickness of the plating layer can be calculated according to the following Faraday's law.

W = (I*t*A)/(n*F)……………………….. (1)

where:

- W= weight of plated metal in grams.
- I= current in coulombs per second.
- t= time in seconds. (30 h(108,000 s))
- A= atomic weight of the metal in grams per mole. (1.008 g/mol for H, 58.693 g/mol for Ni)
- n= valence of the dissolved metal in solution in equivalents per mol.(1 for H, 2 for Ni)
- F= Faraday's constant in coulombs per equivalent. F = 96,485.309 coulombs/equivalent.

So, the equation can be expressed in different form as below.

W = (I*t*A)/(n*F) for Ni plating

W = (I*t*58.693)/(2*96,485)

= 3.042*10^{-4}*I*t

Using equation (1) the answer is:

W = (1*3600*58.69)/(2*96485.309) = 1.09 grams. We are more interested in the thickness of the electroplated metal. In the above equation 1, the thickness of the plating layer can be calculated as follows.

T = (W*10,000)/(rho*S) ….………..….. (2)

where:

- T = thickness in microns.
- rho = density in grams per cubic centimeter. (8.908 g/cm^3 for Ni)
- S = surface area of the plated part in square centimeters.(132.665 cm^2)
- 10,000 is a multiplicative constant to convert centimeters to microns.

If equations 1 and 2 are combined, we have the following equation for plated thickness.

T = (I*t*A*10000)/(n*F*rho*S)………..…… (3)

Assuming that the plating current efficiency is 95% (95% of the cathode current is used for Ni plating and the remaining 5% contributes to the generation of hydrogen) and plating for 30 hours, the following plating layer thickness can be calculated.

T = (I*t*A*10000)/(n*F*rho*S)

= (13.267*0.95*108,000*58.693*10,000)/(2*96,485*8.908*132.665) = 3503.321 microns (3.503 mm)

As a result of the experiment, the plating efficiency reached 99% and the pH was maintained around 4.0 throughout the plating time. A very successful plating without any pits or other defects that had been a problem in the past was obtained as shown Fig. 4.

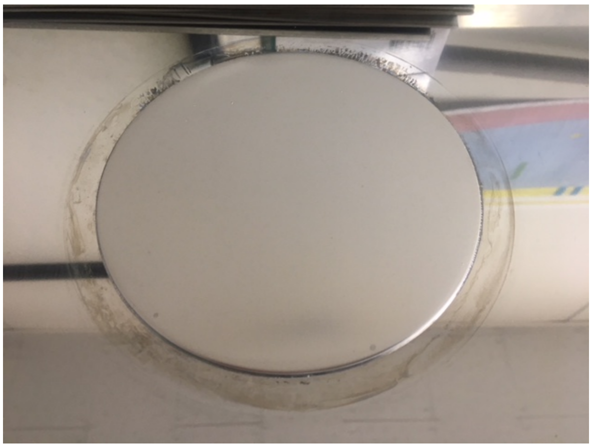


Fig. 4. Ni electrodeposition on type 304 stainless steel plate

3.2 Chemical analysis

The chemical composition requirements of the plating layer specified in Code case N-840 are as follows.

Nickel 99.0% minimum, Silicon 0.01% maximum, Sulfur 0.01% maximum

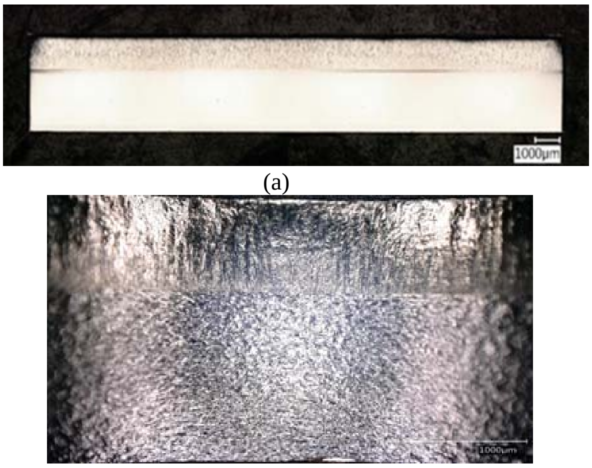
As a result of the analysis, some of the specimens deviate from this specification, and it can be solved through the refinement of the experimental conditions like plating solution preparation. Most of the specimens satisfy the above requirements. Table 2 shows the results of the chemical analysis of each specimen.

Table 2 Chemical analysis result on the Ni deposition

시편 번호	분석 위치	Si	P	S	Ni
NIP BP-4*	center	0.000	0.000	0.006	99.994
NIP BP 4*	side	0.000	0.000	0.006	99.994
NIP BP-10*	center	0.002	0.000	0.016	99.982
NIP BP-10*	side	0.004	0.000	0.039	99.957
NIP BP-13*	center	0.000	0.000	0.003	99.997
NIP BP-13*	side	0.000	0.000	0.008	99.992
NIP BP-15*	center	0.000	0.000	0.007	99.993
NIP BP-15*	side	0.000	0.000	0.007	99.993
NIP BP-16*	center	0.000	0.000	0.006	99.994
NIP BP-16*	side	0.000	0.000	0.005	99.995
NIP BP-17*	center	0.000	0.000	0.005	99.995
NIP BP-17*	side	0.000	0.000	0.006	99.994
NIP BP-18*	center	0.000	0.000	0.007	99.993
NIP BP-18*	side	0.000	0.000	0.006	99.994
NIP BP-19*	center	0.000	0.000	0.004	99.996
NIP BP-19*	side	0.000	0.000	0.004	99.996
NIP BP-20*	center	0.001	0.000	0.004	99.995
NIP BP-20*	side	0.001	0.000	0.005	99.994
NIP BP-23*	center	0.000	0.000	0.007	99.993
NIP BP-23*	side	0.000	0.000	0.007	99.993
NIP BP-27*	center	0.000	0.000	0.017	99.983
NIP BP-27*	side	0.000	0.000	0.015	99.985
NIP BP-28*	center	0.000	0.000	0.006	99.994
NIP BP-28*	side	0.001	0.000	0.006	99.993

3.3 Side bend test

An example of test results (test number BP-4) performed in accordance with ASTM E290 - 'Standard Test Methods for Bend Testing of Material for Ductility', side bend test standard in thin plate, is shown in Fig. 5. The Ni plated layer formed on the 304 stainless substrate is not separated even after the side bend test and shows a very sound adhesion.



(a)

(b)

Fig. 5. Side bend test result on specimen BP-4, (a) before the bending, (b) after the bending (No detachment)

3.4 Wear corrosion resistance evaluation

The wear corrosion rate of the Ni metal in the primary water was evaluated.

In order to satisfy the minimum requirement of cladding layer of 3.2 mm (1/8") in plating, it is possible to produce plating of thickness of 3 mm or more, but since the function of plating layer is to block the exposure of low alloy reactor vessel steel to primary water, it was intended to build up only 1 mm thick layer. The solution for a problem of whether the plated layer can serve as a clad repair even if only 1 mm is used can be found from the following ASME standard on the definition and role of clad.

From ASME IX, "Overlay, Corrosion-Resistant Weld Metal" [4] "Deposition of one or more layers of weld metal to the surface of a base material in an effort to improve the corrosion resistance properties of the surface. This would be applied at a level above the minimum design thickness as a nonstructural component of the overall wall thickness". Cladding provides a non-structural, protective barrier.

Cladding is insured its integrity by evaluating the chemical composition of the plating layer and the interfacial adhesion with the base metal layer without evaluating the mechanical properties of the clad because it needs to have a function not to expose the base metal to primary coolant.

In addition, the corrosion resistance evaluation data of the flow rate can confirm whether the plated layer maintains soundness in the operating environment after repairing.

The wear corrosion rate in the primary water of Ni metal was evaluated through literature analysis [6]. According to W. K. Anderson et al., the wear corrosion rate is 19.4 mg / (dm^2.month) to 50 mg / (dm^2.month) depending on the conditions.

The maximum corrosion rate is about 50 mg / dm^2.month [4]. Based on this reference, the anticipated wear corrosion rate on the Ni plating layer can be predicted. In this experiment, the flow rate is 28 ft/sec., which is similar to the flow rate of 25 ft/sec. (7-8 m/sec.) at the location of the damaged part of the plant.

Since the density of Ni metal is 8.91 g/cm^3, the corrosion rate in the above two cases is 0.0026 to 0.0067 mm/year in the range of wear rate 1 and wear rate 2 as shown in Table 3 below. Even after an additional 40 year operation, wear is 0.10 mm to 0.27 mm, which can prevent exposure of the carbon steel to solution with a thickness of only 1 mm. It has been estimated that it takes more than 149 years for the entire 1 mm thick plating layer to wear out.

Table 3 Wear corrosion rate evaluation on Ni deposit

Density of Ni:8.91g/cm3	Wear rate 1	Wear rate 2
Wear rate, mg/(dm2.month)	50	19.4
Wear rate, g/cm2.month	0.0005	0.0002
Wear rate, mm/year	0.0067	0.0026
Wear for 40 yr operation, mm	0.2694	0.1045
Time to wear out the 1mm thickness,Year	149	383

It is estimated that the corrosion rate is about 0.0067 mm/year, even if the corrosion rate of the two cases predicted in the reference paper is considered, the thickness decrease even after 40 year of operation is only 0.27 mm.

4. Conclusions

- The plating efficiency reached 99% and the pH was maintained around 4.0 throughout the plating time and a very successful plating without any pits or other defects was obtained.
- Most of the Ni plated specimens satisfied the chemical composition requirements.
- The Ni plated layer formed on the 304 stainless substrate was not separated even after the side bend test and showed a very sound adhesion.
- The wear corrosion rate is about 0.0067 mm/year, the thickness decrease even after 40 year of operation is only 0.27 mm.

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