Chromium electroplating and Plasma nitriding to improve the Flow Accelerated Corrosion resistance for the secondary pipe of SMRs

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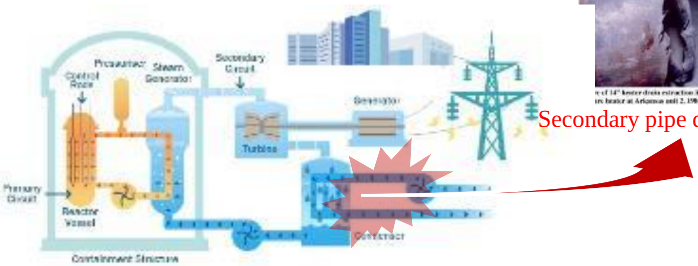
Introduction

Introduction

- **Nuclear power can help with the growing global demand for energy and is becoming an alternative to environmental issues such as carbon neutrality.**
- **Small Modular Reactor** (**SMR**) :
  - a power capacity of 300 MWe or less.
  - power supply, cogeneration, seawater desalination, and hydrogen production.
    (industrial area, special facilities, remote area, and etc…)
  - high safety and reliability by inherent safety and passive safety system.
  - economic : low cost and short period by modularity.
- **Degradation** (corrosion, erosion, and etc…)
  - miniaturization, secondary system extension, difficulty in periodic maintenance.
- **Prevent degradation technologies:**
  - replacement of material
  - control hydro-chemical parameter
  - <u>surface treatment.</u>

Canadian Roadmap for SMR (2018)



Secondary pipe degradation prevention

Experimental

Experimental

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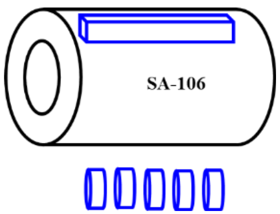
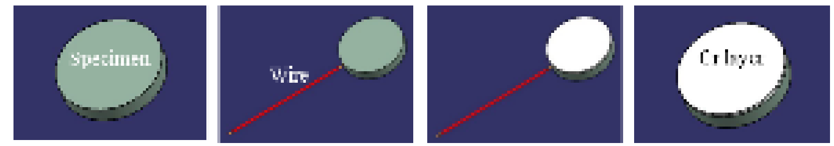




Cutting
The carbon steel tube (SA-106) to disk specimen (12ø, 2mm)

→

Polishing
The test surface with 0.25μm diamond suspension

→

Welding
Edge of the specimen with wire

↓

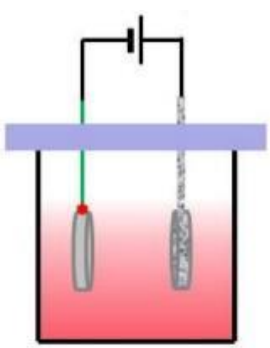
Chromium electroplating
In sargent bath

→

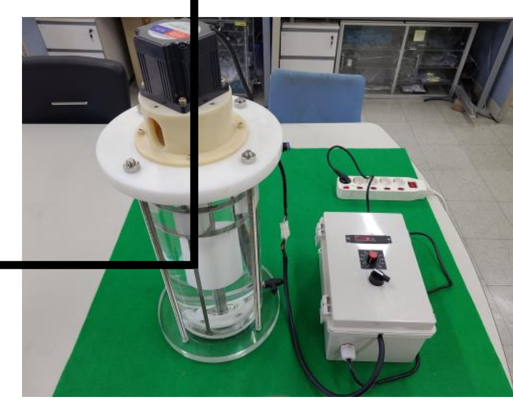
RF power plasma nitriding
At 600℃, 500W

→

FAC test
In deionized water and 3.5 wt.% NaCl solution.



Measurement
of the mass change



Results

Chromium Coating with Electroplating

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- **Chromium Coating**
  - Electrolyte (Sargent soln) : $CrO_3 + H_2SO_4$
  - Cathode (Material) : $CrO_4^{2-} + 8H^+ + 6e^- \rightarrow Cr + 4H_2O$
  - Anode (Pb-Sn alloy) : $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

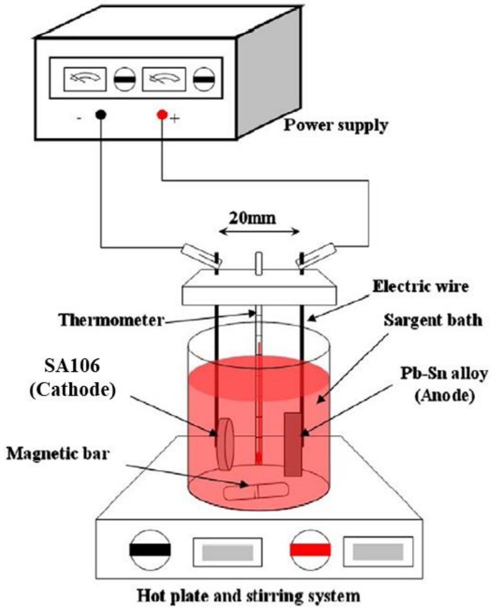
Table. 1. Carbon steel SA-106 chemical composition

C	Si	Mn	P
0.19	0.25	0.98	0.012
S	Cu	Cr	Ni
0.004	0.02	0.04	0.03
Mo	Ti	Nb	
0.01	0.001	0.008	

\- Changes in plating layer properties according to **temperature** and **current density**.

⇒ **Select suitable plating conditions for the purpose of use.**

- **Test Conditions**
  - Substrate : SA-106 Gr.B (Ø : 12 mm, t : 2 mm)
  - Specimen polishing : 0.25 μm diamond suspension
  - Anode material : Pb-Sn alloy (9:1 wt%)
  - Sargent bath : Chromic trioxide 250 g/L, H_2SO_4 2.5 g/L
  - Volume of bath (mL) : 100
  - Stirring speed in bath (rpm) : 150
- **Variable**
  - Current type : DC, PC (50%)
  - Current density (A/dm^2) : 44 ~ 354
  - Quantity of electric charge (C) : 300 ~ 4,800
  - Temperature (°C) : 50, 60, 70, 80



A schematic diagram of Chromium Electroplating

Chromium Coating with Electroplating

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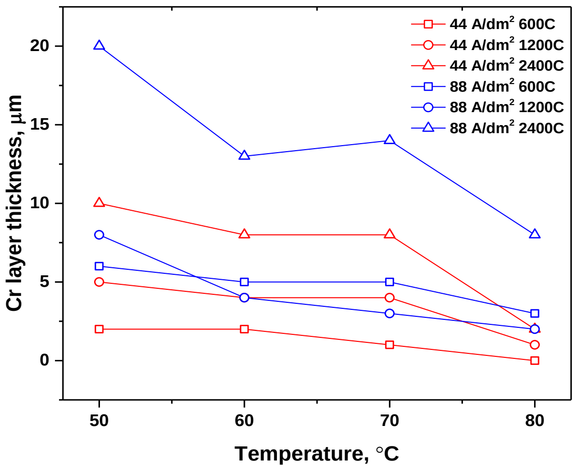
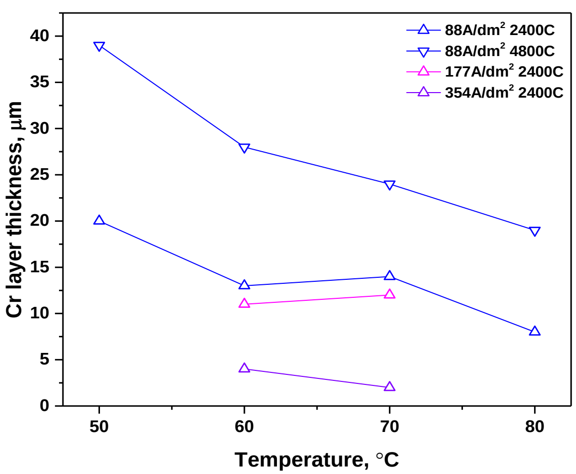
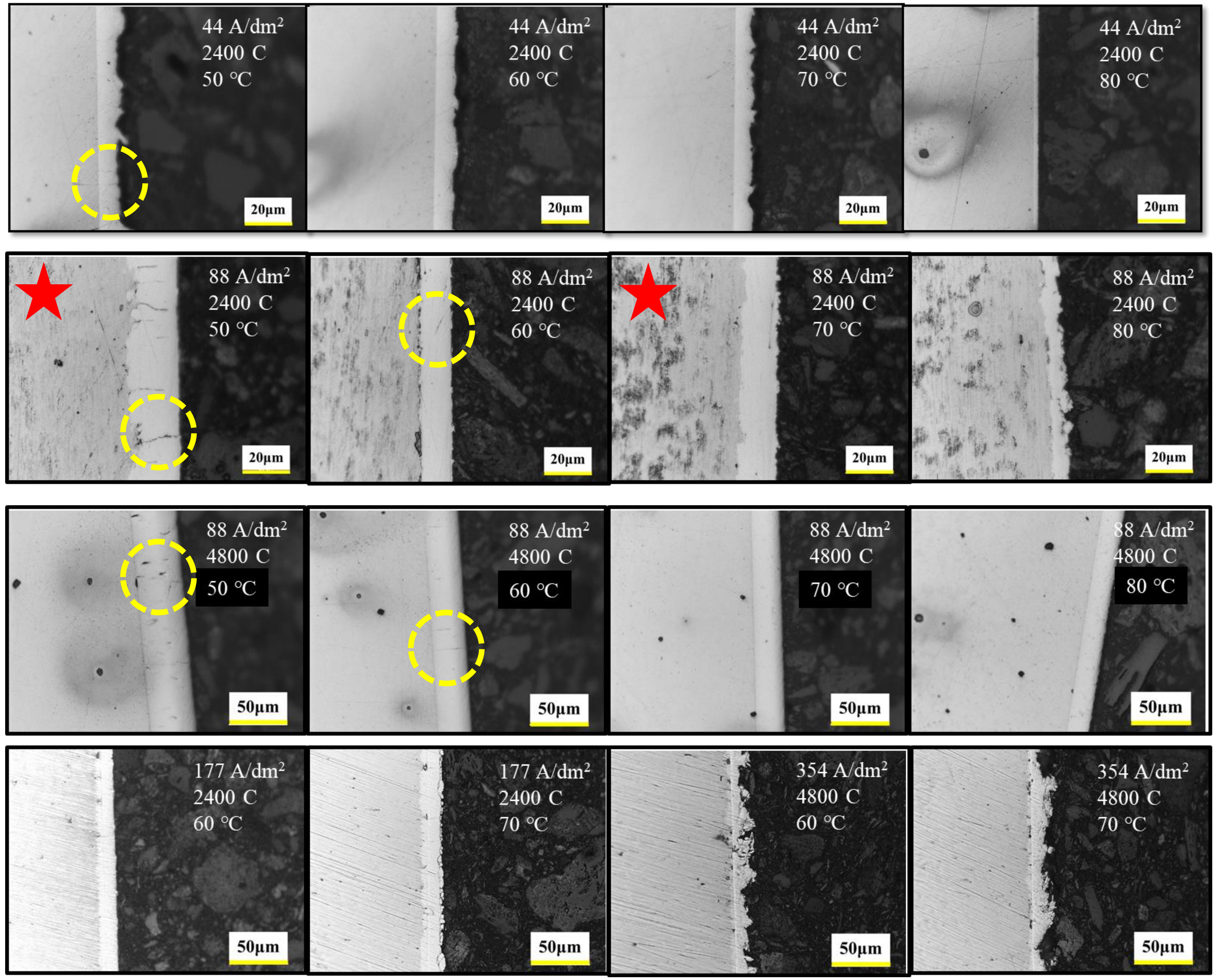
➢ Cr coating layer Results







A Cross-sectional micrographs under various plating conditions.

✓ Satisfy coating layer ? Fast ? Uniform surface ?

⇒ **Cr coating conditions : 88 A/dm², 2400 C – 50 & 70 °C**

RF power Plasma Nitriding

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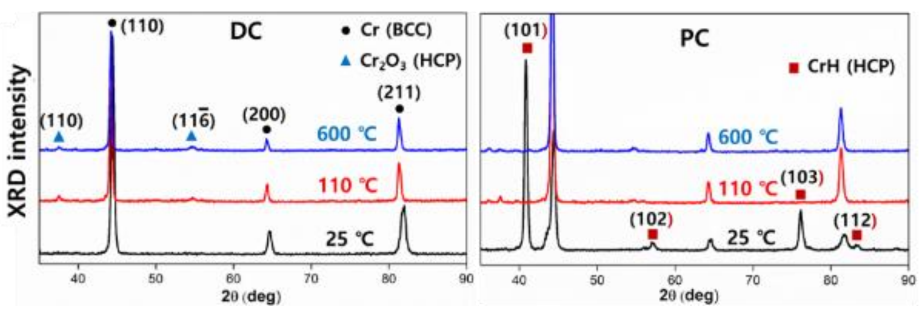
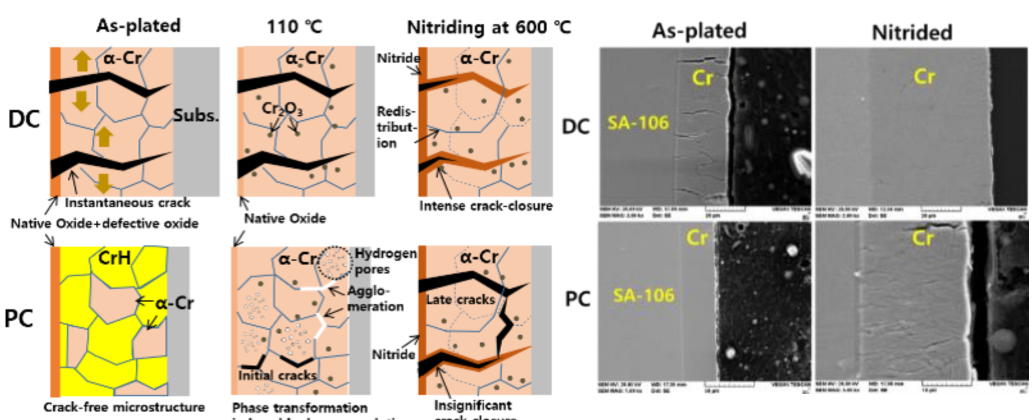
- **Test conditions**
  - Power (W) : 180, 500 W
  - Temperature (℃) : 600
  - Frequency : 13.56 MHz
  - Internal pressure : ~ 10^{-2} Pa
  - N2-H2 mixed gas ratio : 60:40 in vol.%
  - Gas flow rate (sccm) : 20
- **Variable**
  - Test time (h) : 10 ~ 20

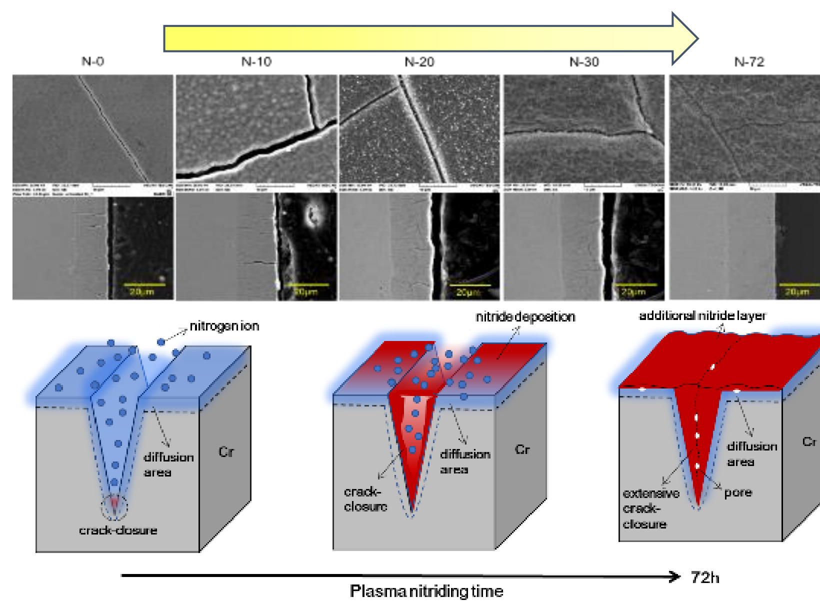
RF power Plasma Nitriding equipment



The XRD pattern of DC and PC-60 Cr coated SA-106 after heat treatment



Defeat occurred and phase transformed after heat treatment at 110℃ and plasma nitriding at 600℃

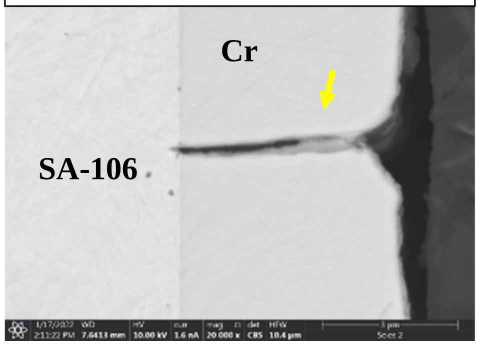


A SEM profile of the recovery of cracks in Cr coated as the nitriding process time increases

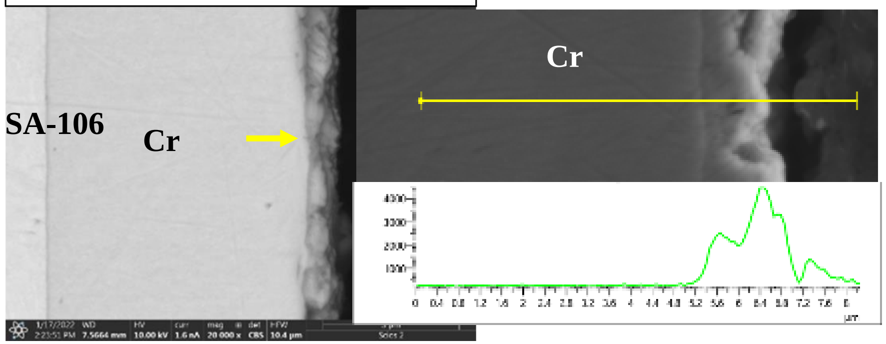
RF power Plasma Nitriding

➢ Cr-N coating layer Results

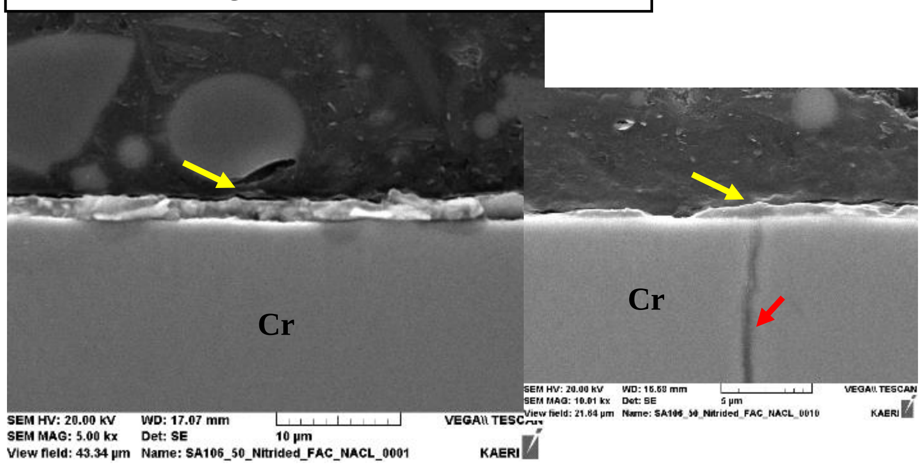
Cr-electroplated: DC, 50°C, 1200C, 88A/dm²
Plasma Nitriding: 600°C, 500W, 10h.



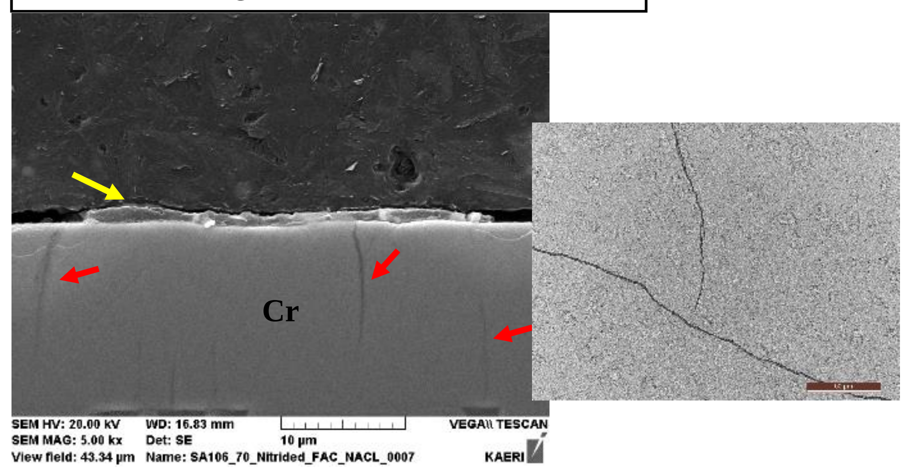
Cr-electroplated: DC, 70°C, 1200C, 88A/dm²
Plasma Nitriding: 600°C, 500W, 10h.



Cr-electroplated: DC, 50°C, 2400C, 88A/dm²
Plasma Nitriding: 600°C, 500W, 10h.



Cr-electroplated: DC, 70°C, 2400C, 88A/dm²
Plasma Nitriding: 600°C, 500W, 10h.



A micrographs of cross-sections by SEM of Cr/N double layer

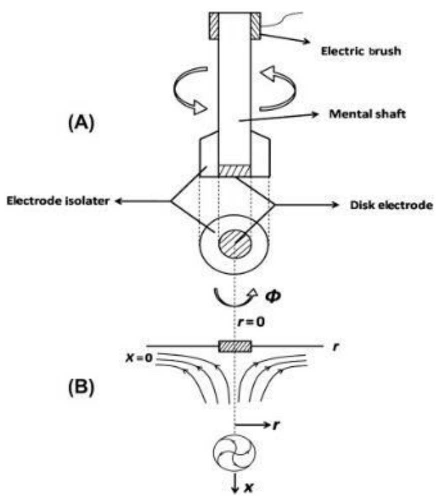
⇒ 88 A/dm², 2400 C, 50 °C : micro-cracks <u>recovered</u> and Cr/N nitride formed

⇒ 88 A/dm², 2400 C, 70 °C : micro-cracks <u>occurred</u> and Cr/N nitride formed

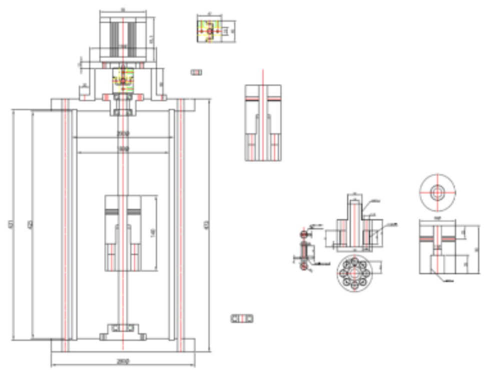
Flow Accelerated Corrosion test

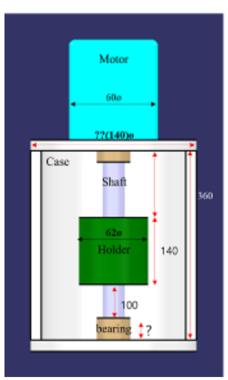
- **Cr/N double coating layer performance screening test**
- Corrosion and erosion behavior evaluation

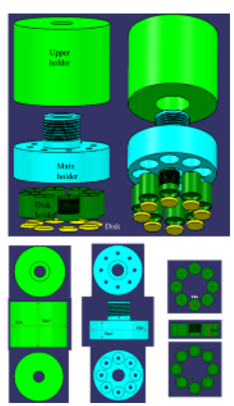
- Design and manufacture of FAC simulation test equipment
- Maximum speed : 4000rpm
- Accelerated Test (artificial seawater, Al_2O_3 suspension)

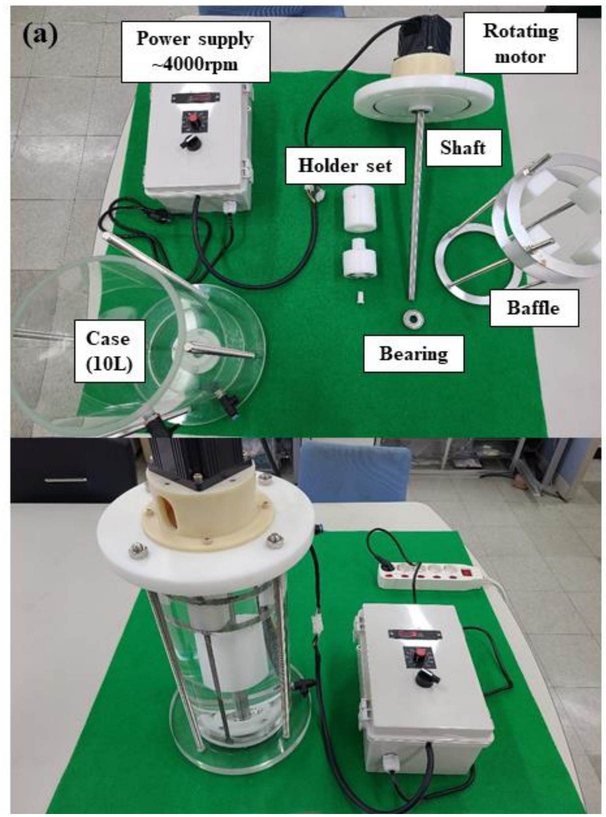


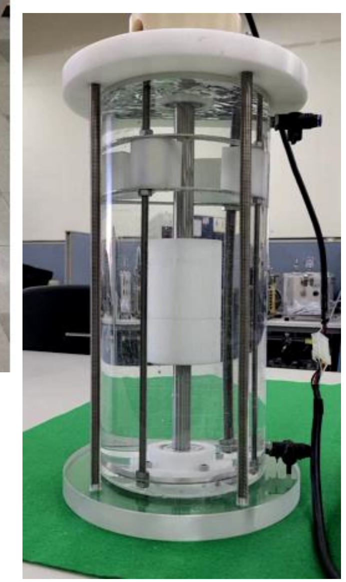
A Schematic diagram for convection of Rotating Disk electrode (RDE)







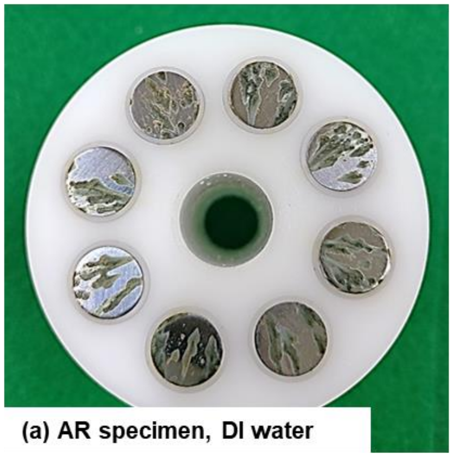




Flow Accelerated Corrosion test

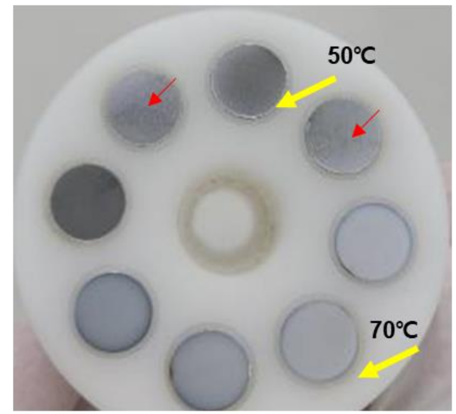
- **Test conditions:**
  - Temperature (℃) : RT (~25)
  - Solution: Deionized water, Artificial sea water (3.5 wt% NaCl), Al_2O_3 1,000 ppm
  - Speed of revolution (rpm) : 2,000 (4.61 m/s)
  - Test time (h) : 5

◆ Stationary state (5hr)



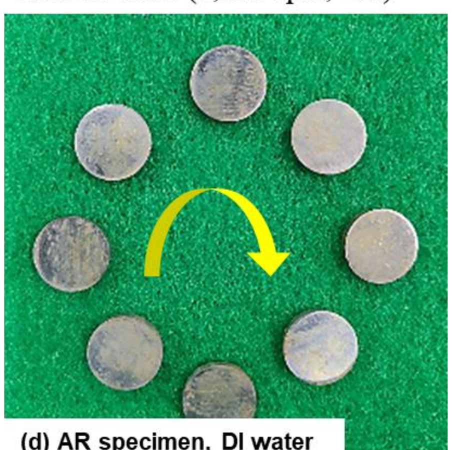
(a) AR specimen, DI water

(b)AR specimen, 3.5 wt% NaCl solution



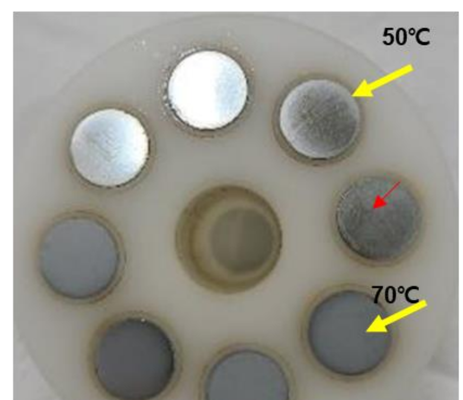
(c) Cr Coated specimen, 3.5 wt% NaCl solution

◆ Rotated state (2,000 rpm, 5hr)



(d) AR specimen, DI water

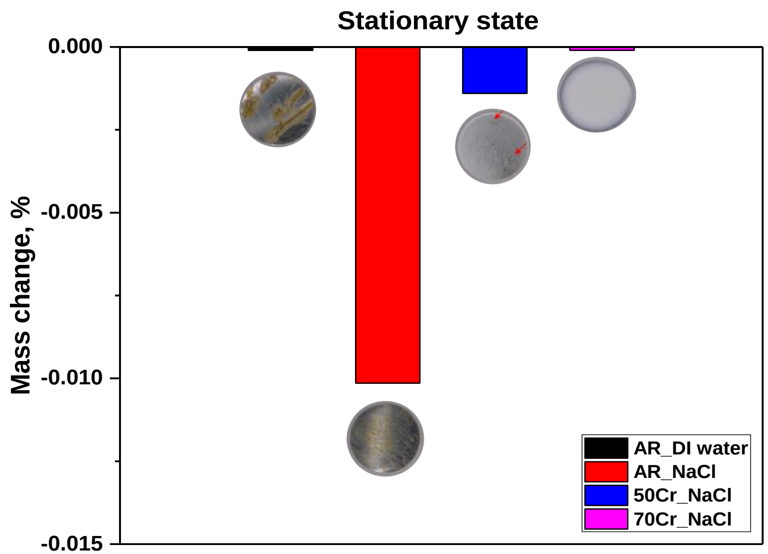
(e) AR specimen, 3.5 wt% NaCl solution

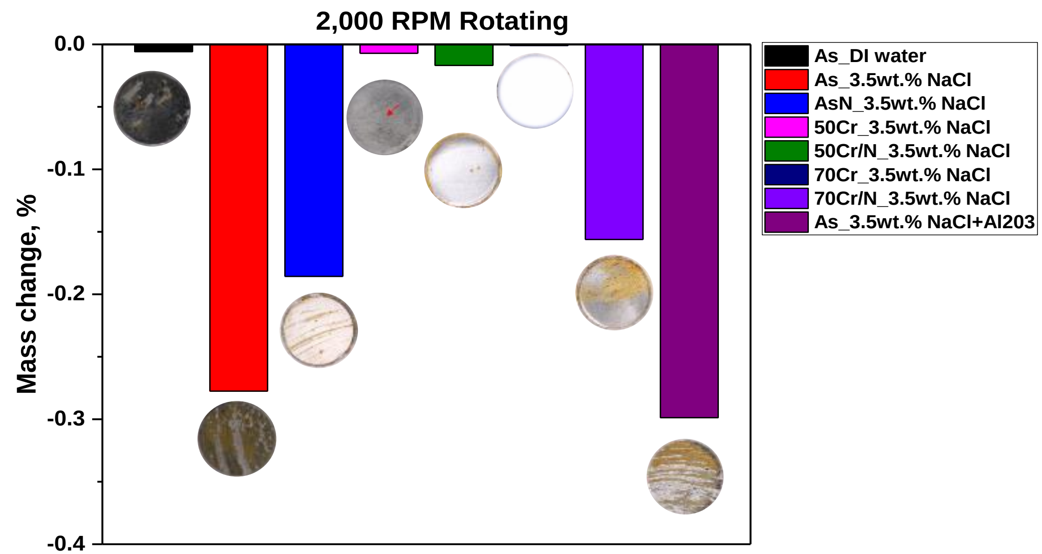


(f) Cr Coated specimen, 3.5 wt% NaCl solution

Flow Accelerated Corrosion test

- **FAC test results**





*AR: As received specimen
*Cr: 00 °C Cr coated
*Cr/N: Cr coated and nitriding

⇒ **Mass change – Stationary state : (NaCl) AR > 50℃ Cr coated > 70℃ Cr coated**

– Rotating : (NaCl) AR > 50℃ Cr coated > 70℃ Cr coated

(NaCl) AR N > 70℃ Cr/N > 50℃ Cr/N

⇒ **The weight loss of the Cr/N layer is greater than the Cr single layer. However, the non-nitrided part must be considered.**

Summary

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- ✓ Cr-Electroplating and nitriding methods were studied and conditions were selected to prevent degradation of secondary system piping of nuclear power plant.
- ✓ 88 A/dm2, 2400 C – Cr layer thickness: 20 μm at 50 °C, 13 μm at 70 °C
- ✓ FAC resistance was the highest in the condition of crack-free Cr-coating at 70 °C.
- ✓ The Cr-coated specimen at 50 °C recovered cracks after the nitriding at 600 °C, but Cr-coated at 70 °C cracked.
- ✓ Electroplating and nitrided specimens cause more weight loss than electroplating only.
- ✓ For specimens plated at 50 °C, there is a possibility of improvement.

❖ In the future, additional experiments will be conducted and analyzed by changing the solution conditions.

References

[1] HAN, Dengcheng, et al. A Multi-Stochastic SMR Siting Model Applied to the Province of Saskatchewan, Canada: Emphasis on Technological Competition and Policy Impacts. Resources, Conservation and Recycling, Vol. 178, 2022, 106059.
[2] BHOWMIK, Palash Kumar; SCHLEGEL, Joshua Paul, Multicomponent gas mixture parametric CFD study of condensation heat transfer in small modular reactor system safety. Experimental and Computational Multiphase Flow, 2022, 1-14.
[3] OLATEJU, Babatunde; KUMAR, Amit; SECANELL, Marc, A techno-economic assessment of large scale wind-hydrogen production with energy storage in Western Canada. International Journal of Hydrogen Energy, Vol. 41, Issue 21, 2016, Pages 8755-8776.
[4] COOPER, Mark, Small modular reactors and the future of nuclear power in the United States. Energy Research & Social Science, Vol. 3, 2014, Pages 161-177.
[5] Chexal, B., Horowitz, J., & Dooley, B, Flow-accelerated corrosion in power plants, Revision 1 (No. EPRI-TR-106611-R1). Electric Power Research Inst., Palo Alto, CA (United States); Electricite de France (France); Siemens AG Power Generation (Germany), 1998
[6] Lee, Y. B., Lee, J. M., Hur, D. H., Lee, J. H., & Jeon, S. H, Effects of Advanced Amines on Magnetite Deposition of Steam Generator Tubes in Secondary System, Coatings, 2021, 11(5), 514
[7] De Bouvier, O., Bouchacourt, M., & Fruzzetti, K, Redox conditions effect on flow accelerated corrosion: Influence of hydrazine and oxygen, 2002
[8] Sugino, W., Ohira, T., Nagata, N., Abe, A., & Takiguchi, H, Effect of water chemistry improvement on flow accelerated corrosion in light-water nuclear reactor, 2009
[9] Yang, S. W., Ryu, H. J., Kim, J. H., Lee, B. O., & Lee, C. B, FCCI barrier performance of electroplated Cr for metallic fuel", Journal of nuclear materials, 2010, 401(1-3), 98-103
[10] T. H, Webersinn and J. M. Hosdowich, Research Report No. 128, United Chromium, New York, 1932
[11] Du, C., Tan, Q., Yin, G., & Zhang, J. (2014). "Rotating disk electrode method", In Rotating Electrode Methods and Oxygen Reduction Electrocatalysts (pp. 171-198). Elsevier
[12] Yang, S. W., Ryu, H. J., Kim, J. H., Lee, B. O., & Lee, C. B. (2010). "FCCI barrier performance of electroplated Cr for metallic fuel", Journal of nuclear materials, 401(1-3), 98-103

Thank you for listening

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