Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2023

Optimization of electroplating process using pulse reverse current for enhanced FCCI barrier property on metallic fuel cladding

Sung Su Ryu [a, b], Jeong Mok Oh [a], SungHwan Yeo [a], Sung Ho Kim [a], Young-Kook Lee [b], Jun Hwan Kim [a*]
[a]*Advanced Fuel Technology Development Division, Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 34057, Republic of Korea*
[b]*Department of materials science and engineering, Yonsei University, 50 Yonsei-ro, Seondaemun-gu, Seoul, 03722, Republic of Korea*
[*]*Corresponding author: junhkim@kaeri.re.kr*

1. Introduction

A sodium-cooled fast reactor (SFR), a generation-IV reactor, has advantages such as reuse of nuclear fuel, reduction of spent fuel volume and management period of spent fuel, and significant improvement in nuclear fuel utilization through recycling. Therefore, nuclear-advanced countries are pushing for the full-scale development of SFR with emphasis on sustainability, economic feasibility, proliferation resistance, and inherent safety [1].

However, the metallic fuel causes fuel-cladding chemical interaction (FCCI) at temperature above 650℃ which forms low meting point eutectic compounds and reduces the thickness of fuel cladding [2]. FCCI undermines the safety of the reactor when using metallic nuclear fuel. Therefore, various studies have been conducted to prevent FCCI. The method to prevent FCCI can be broadly classified into three categories. The first method to prevent FCCI is to add a trace amount of dopant to metallic fuel to prevent the material diffusion [3]. The second method is to form a physical Zr or V liner between the fuel and cladding to prevent material diffusion [4]. Lastly, there is a method of coating the inner surface of the cladding to prevent material diffusion [5]. Our research team has been conducting studies on cladding inner surface coating, and in particular, we have been consistently studying to form a reliable chrome (Cr) coating layer using electroplating. However, currently, there is no research on the reliability of the coating layer and FCCI resistance affected by the pulse reverse (PR) current during electroplating on the inner surface of cladding. Therefore, in this study, we optimized the inner surface of cladding electroplating using PR current compared the microstructure and FCCI resistance with the commonly used Direct Current (DC) [6]. Based on this study, we determined the electroplating current waveform to be used in future scale-up studies.

2. Experimental methods

HT9 disks which are generally used for metallic fuel cladding tubes were used as substrate. Each disk was of 12 mm diameter and 2 mm thick. The electroplating apparatus composed electroplating bath, a power supply, as thermometer, a stirring and heating system, and etc. (fig. 1). A Sargent bath containing 250 g/l of chromic acid (CrO_3) and 2.5 g/l of sulfuric acid (H_2SO_4) was used as an electrolyte. The temperature of the electrolyte was maintained at 55 ℃ with magnetic stirring (at 150 rpm) on a hot plate. A Pb-Sn alloy was used as the anode metal.
After cutting each Cr coated disk, it was mounted to measure the thickness of the coating layer. The thickness of Cr coatings was investigated using Optical Microscopy (OM). The hardness of Cr coatings was measured using a micro-Vickers hardness tester (ASTM E92-17). To calculate the average thickness of the coating layer, hardness and standard deviation values, at least 5 measurements were obtained per specimen. We conducted diffusion couple test to evaluate the FCCI resistance of the Cr coating layer. We attached and fixed it to the coated HT9 disk using bolts, and after inserting it for 25 hours and 650 ℃, we analyzed the inter-diffusion area using Scanning Electron Microscopy (SEM).

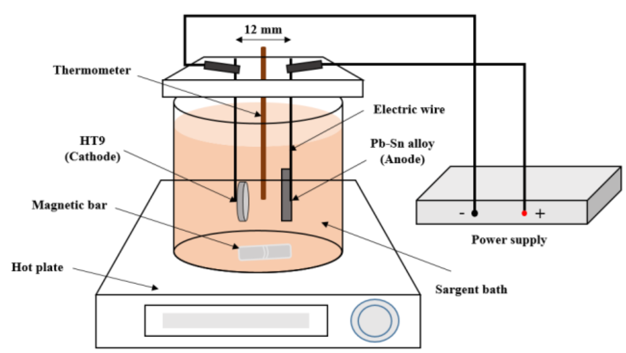

Fig. 1. Setting up a Cr electroplating devices.

3. Results and discussion

3.1. Process optimization

The electrodeposition process is sensitive to changes in parameters such as bath temperature, time (T), current density (I) and current waveform. In this study, the optimal coating thickness was determined to be 20 μm based on previous research [7]. Through experiments, we found the optimal condition of the DC and PR electroplating. The results shows that the optimized conditions are 55 ℃, 70 minutes, and a current density of 1.06 A/cm^2.

The FCCI barrier property was affected by the grain structure of the coated Cr. In this experiment, we changed the duty cycle (γ) [8]. The experimental results showed that a duty cycle of 0.9990 was the optimal condition. The duty cycle is shown as follows:

$$\gamma = \frac{T_{on}}{T_{on} + T_{off}} \quad (1)$$

Table 1. Experimental cases.

Experiment	*Temperature/℃*	*Time/min*	*Ia/A cm^{-2}*	*Ic/A cm^{-2}*	*T_{on}/msec*	*T_{off}/msec*
1	50	40	0.88	0	1	0
2	75	40	0.88	0	1	0
3	55	40	0.88	0	1	0
4	55	70	0.88	0	1	0
5	55	70	2.03	0	1	0
6	55	70	1.50	0	1	0
7	55	70	1.06	0	1	0
8	55	70	1.06	0.27	100	1
9	55	70	1.06	0.27	500	1
10	55	70	1.06	0.27	900	1
11	55	70	1.06	0.27	1000	1
12	55	70	1.06	0.27	1100	1

3.2. Microstructural analysis

Fig. 2 shows that OM images of Cr coating layers using DC and PR. As shown, the Cr coating layers using PR has the different surface grain morphology and a crack-free layer. In case of using PR, Cr coatings have small grains and crack-free. The measured hardness vales clearly showed the inverse relationship between grain size and hardness of Cr coatings. By adjusting the duty cycle, it is possible to increase suitable nucleation positions of each cycle, resulting in the creation of a fine-grained Cr coating layer and a reduction in internal stress due to the increase in fine-grained boundaries [9]. As a result, it exhibits lower hardness compared to DC. Fig. 3 shows the low FCCI resistance at 20 μm using DC. The reason why many cracks occurred in DC resulted in decreased FCCI resistance. Since there are no cracks when using PR, it has better FCCI resistance compared to DC.

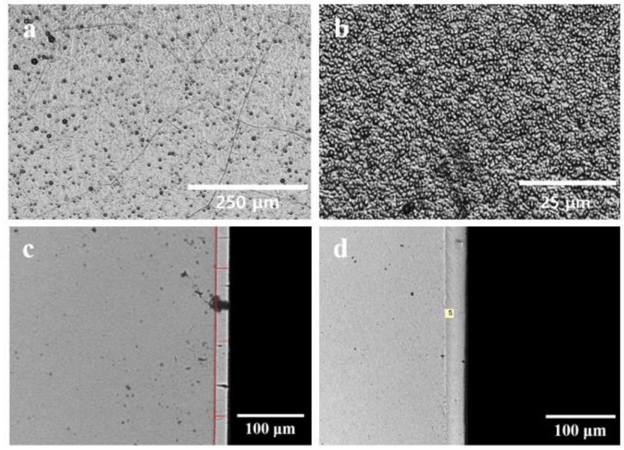

Fig. 2. Surface morphology and cross section images of Cr coatings obtained by (a and c) DC and (b and d) PR.

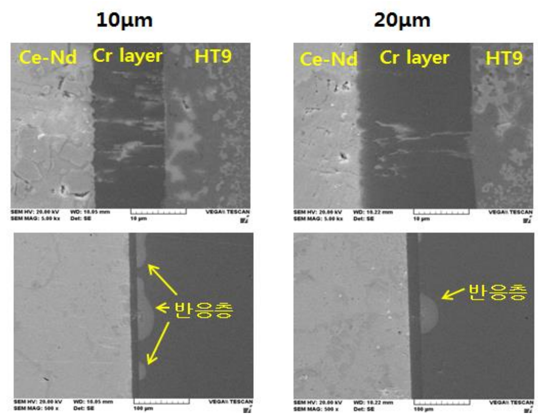

Fig. 3. SEM micrographs of diffusion couple tested Cr barrier coated HT9 disks electroplated using DC.

4. Conclusion

This study analyzes the microstructural features and FCCI resistance through PR optimization. The conclusions of this study are as follows:

1) The optimized PR conditions are 55 ℃, 70 minutes, and a current density of 1.06 A/cm^2. 2) In terms of morphology, the Cr coatings using PR current electroplating was crack-free unlike DC with many cracks. Additionally, the Cr coatings using PR showed better FCCI resistance than DC due to the small grain size. 3) Despite forming a 20 μm thickness, the FCCI test results showed that DC conditions had lower FCCI resistance due to the presence of many cracks.

REFERENCES

[1] J.S. Cheon, S.J. Oh, B.O. Lee, J. Nucl. Mater. 385 (2009) 559.

[2] K. Nakamura, T. Ogata, M. Kuruta, T. Yokko, M.A Mignanelli, J. Nucl. Sci. Technol. 380 (2001) 112.
[3] D.W. Egeland, R.D. Mariani, T. Hartmann, Journal of Nuclear Materials 440 (2013) 178–19

[4] D.D. Keiser, J.I. Cole, An Evaluation of Potential Liner Materials for Eliminating FCCI in Irradiated Metallic Nuclear Fuel Elements (2007)
[5] R.A. Clark, M.A. Conroy, npj materials Degradation (2020) 4
[6] S.H. Yeo, C.M. Lee, Applied Surface Sscirence (2022) 152133
[7] S.H. Yeo, J.H. Kim, Surface and Coating Tech. 389 (2020) 125652
[8] D.W. Lim, B.I. Ku, D.J. Seo, C.W. Lim, International Journal of Refractory Metals & Hard Materials. 89 (2020) 105213.
[9] M.R. Saghi Beyragh, S. Norouzi, Surface and Coatings Tech. 205 (2010) 2605-2610