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Experimental Study on High Temperature Oxidation Behavior of ESPER^{TM} Cr-coated Cladding

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1. Introduction

Accident Tolerant Fuel (ATF) has been developed to enhance the safety and performance of nuclear fuel compared to traditional UO_2 fuel and zirconium alloy cladding used in Light Water Reactors. The development of ATF gained momentum following the Fukushima nuclear accident in 2011, with the primary objective of significantly improving fuel safety under severe accident conditions [1-2]. KEPCO Nuclear Fuel(KNF) is currently developing of commercial technology under the ESPER(Enhanced Safety Performance with Efficiency and Reliability) project, as ATF solution intended for near-term application. Chromium-coated zirconium alloy is among the most promising candidates for ATF cladding in LWRs [3-4]. It is important to note that Cr coatings, typically produced through various methods, function as effective diffusion barriers against oxygen ingress. However, the protective efficacy of these coatings is highly dependent on the appropriate selection of coating thickness and the environmental temperature to which the material is exposed. Accordingly, this study analyzes the effects of coating thickness selection for ESPER cladding and examines the oxidation behavior under different exposure temperatures, durations, and heating rates in a high-temperature steam environment.

2. Methods and Results

2.1 Coating Thickness

To evaluate the effect of coating thickness, cladding with various thicknesses was produced using a commercial arc ion plating system on a 4-meter scale, following the same process as that used for commercial coating cladding. High-temperature oxidation tests were conducted on these samples using a simultaneous thermal analysis device to determine the optimal coating thickness. The tests were performed in a steam atmosphere at 1200°C for approximately 1000 seconds. The results, presented in Figure 1, indicate that coating thicknesses below approximately 5 µm did not exhibit any oxidation delay effect. In contrast, for thicknesses above this value, similar high-temperature oxidation behavior was observed over the 1000-second duration, regardless of the specific thickness. Consequently, taking into account manufacturing tolerances and measurement errors, the coating thickness for commercial cladding was selected to be in the range of 10-20 µm.

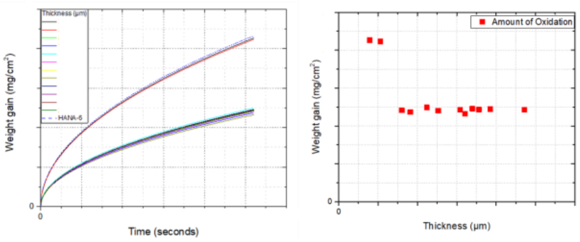


Fig. 1. High-temperature oxidation test results for different coating thicknesses at 1200°C for 1000 seconds.

2.2 Oxidation Behavior

High-temperature oxidation tests were conducted on prototype chromium-coated cladding in a steam atmosphere at 1300°C and 1350°C. To rapidly reach the target temperature, the furnace was preheated in a steam atmosphere, and the specimens were then introduced. The heating rate averaged 17°C per second until the target temperature was achieved, with no overshoot, thanks to precise control characteristics. At 1300°C, as shown in Figure 2, the outer chromium coating retained its protective function for 12 minutes. This behavior is consistent with previous research [5], where the heating rate reached up to 20°C per minute in an inert atmosphere before steam. When comparing the oxide layer thicknesses on the inner and outer surfaces, the zirconium surface on the inner side measured approximately 100 µm, while the chromium surface on the outer side measured 8.36 µm. This confirms a high-temperature oxidation rate difference of about 15 times, considering the Pilling-Bedworth Ratio.
To evaluate the high-temperature oxidation behavior above the chromium-zirconium eutectic temperature, additional steam oxidation tests were conducted at 1350°C. As shown in Figure 3, "alligator skin [6]" patterns were observed on the surface after 3 minutes of exposure, with partial chromium oxide layers, chromium-zirconium oxide layers, and zirconium oxide layers forming on the outer surface. Additionally, the similar weight gain observed between the chromium-coated cladding and zirconium cladding suggests that

the delayed oxidation effect of chromium above the eutectic temperature is minimal. Therefore, performance degradation of the chromium coating occurs above the eutectic point, and post-degradation performance is similar to that of the base material.

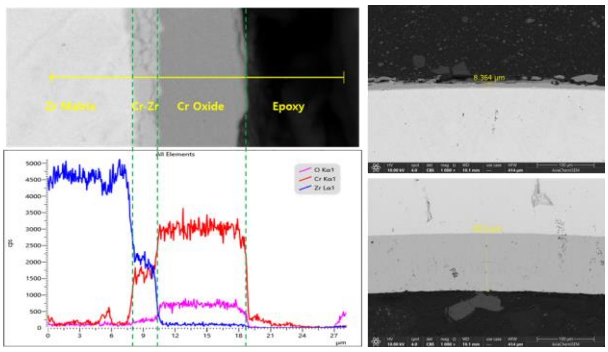
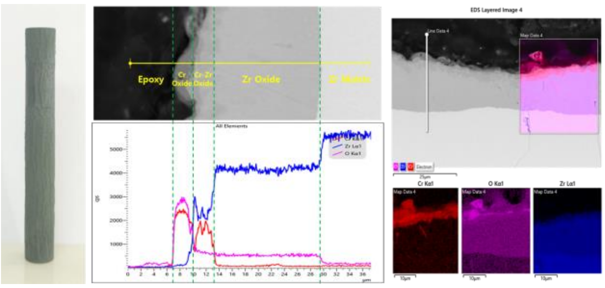


Fig 2. Results for cross-sectional analysis after HT oxidation test at 1300°C – 12 min.



(a) (b) (c)

Fig 3. Results for (a) appearance and cross-sectional analysis ((b) line scanning and (c) mapping) after HT oxidation test at 1350°C – 3 min.

3. Conclusions

This study examines the behavior of chromium-coated cladding in high-temperature oxidation environments with steam. The results of high-temperature steam oxidation tests at 1200°C on the ESPER chromium-coated cladding, developed by KNF, indicate that a chromium layer above a certain thickness provides protection for up to 1000 seconds. Moreover, at 1300°C, the chromium layer demonstrated approximately 15 times the high-temperature oxidation delay effect compared to the zirconium surface, maintaining a protective layer for up to 12 minutes. However, above the eutectic temperature, the delayed oxidation effect of chromium is diminished, and the behavior of the material becomes similar to that of the base substrate. Future research will focus on evaluating the behavior of ESPER chromium-coated cladding under more extreme conditions and conducting additional studies aimed at delaying or preventing degradation.

4. Acknowledgements

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