Analysis of Mechanical Properties of Cladding Tubes with Varying Coating Thickness

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1. Introduction

The significance of nuclear power plant safety has been emphasized after the Fukushima accident. Specifically, there has been increased focus on developing technologies for the commercialization of Accident Tolerant Fuel (ATF). In Loss of Coolant Accident (LOCA) scenario, high-temperature steam oxidation of the fuel cladding can occur before the coolant system activates [1,2]. This, coupled with the pressure differential between the inside and outside of the cladding, could potentially lead to ballooning and burst.

In order to develop ATF, the main requirement of ATF which extends coping time and reduces generation of hydrogen has to be achieved. The chromium has excellent capabilities of high temperature oxidation resistance, corrosion resistance, and reducing generation of hydrogen [3]. For this reason, the chromium (Cr) coating is being considered as one of ATF candidates.

According to the US NRC [4], the use of coated cladding in ATF fuel rods will require changes to the existing Specified Acceptable Fuel Design Limits (SAFDLs) due to new degradation mechanisms. In particular, coating cracking and delamination significantly impact the extension of coping time and the reduction of hydrogen generation, which are main requirements for ATF. Therefore, key evaluation parameters such as high-temperature ballooning behavior, fuel rod ballooning, high-temperature steam oxidation rate, cladding fatigue properties, and cladding embrittlement must be assessed. To support these evaluations, research providing quantitative values for the adhesion strength between the substrate and coating is essential.

In this research, two types of Cr-coated zirconium alloy claddings are quantitatively compared through the hardness which is majorly used for measuring material properties and adhesion of coating from nano-indentation tests at substrate, Cr-coating, and interface between substrate and Cr-coating.

2. Test Methods and Results

2.1 Test Procedure

Specimen preparation for the nano-indentation test was conducted as follows. First, each cladding was hot-mounted using a carbon-based powder. After hot mounting, Specimens were flattened from low number (#400) to high number sand paper and polished with diamond suspension. Following instrument in Fig.1 is used for nano-indentation test. After performing tests, the tested locations were examined using Scanning Electron Microscope (SEM).

Fig. 1. Nano-indentation instrument

2.2 Material and Test Specimen

For the ATF, zirconium alloy cladding was coated using an arc ion plating facility. The chromium was deposited on the outer surfaces of cladding tube. In order to confirm the effect of two coating thickness on coating adhesion, two types of coating thickness were selected as the production of Cr-coated cladding shown in Table I.

Table I: Specimen cases

Case	Coating Thickness (μm)	Substrate
Case 1	18	Zirconium alloy
Case 2	11	

2.3 Nano-indentation Test Results

As shown in Fig 2, it was confirmed that the hardness and elastic modulus of substrate shows maintained properties after different coating procedure for different coating thickness.

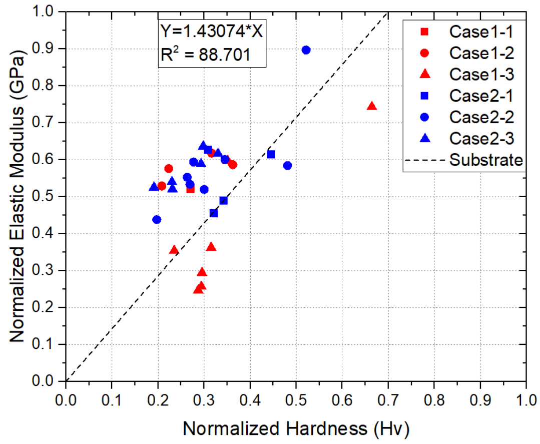

Fig. 2. Nano-indentation test results (Substrate)

In Fig 3, through comparison of the coating thickness, it was confirmed whether there was no difference in results depending on the conditions. Cr coating were indented from a surface of coating to a interface between substrate.

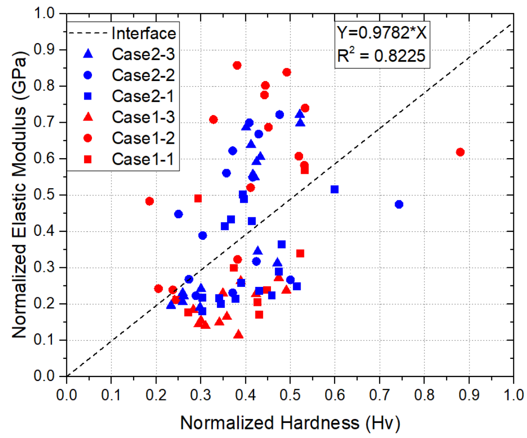

Fig. 3. Nano-indentation test results (Coating and Interface)

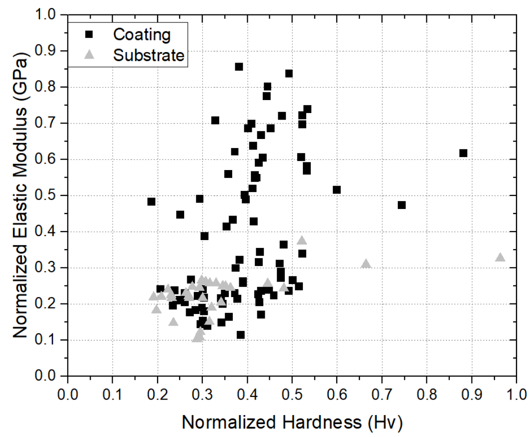

Fig. 4. Nano-indentation test results (Substrate, Coating, and Interface)

In Fig 4, through comparing substrate with coating and interface, it was figured that coating and interface has significantly high hardness than substrate and after tests there is no delamination or crack on indent target as shown in Fig.5.

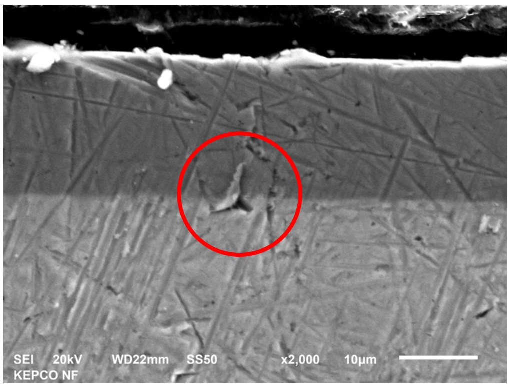

Fig. 5. SEM analysis on Nano-indentation test (Interface)

3. Conclusions

In this study, nano-indentation test results according to the coating thickness of the ATF Cr-coated cladding were compared. The results can be classified into two categories.

Firstly, differences in coating time arise depending on the thickness of Cr-coating. However, it was confirmed that the process time difference between 11 and 18 µm does not significantly affect the strength of substrate or the adhesion strength. Because changes in substrate and coating during the coating process are not prominent.

Second, when comparing the hardness with that of substrate, the Cr-coating exhibited high strength, indicating that its adhesion is not compromised. This is further demonstrated by an SEM analysis conducted after the nano-indentation test, which showed no delamination of the coating.

Therefore, Cr-coated cladding tubes manufactured using an arc ion plating process show minimal differences in adhesion and hardness despite variations in coating thickness, while offering significantly enhanced hardness compared to the substrate.

ACKNOWLEDGEMENT

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