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Application of Coating Technology for Accident Tolerant Fuel Cladding

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1. Introduction

Many efforts have being focused on the fuel cladding development to increase the safety margin of nuclear fuel during the accident conditions in a LWR's after the Fukushima accident [1-7]. Various accident tolerant fuel (ATF) cladding concepts are considered and have being developed to increase the oxidation resistance and ballooning/rupture resistance of current Zr-based cladding material under accident conditions. From the recent research trends [1-7], the ATF cladding concepts for enhanced accident tolerance are divided as follows: Mo-Zr cladding to increase the high temperature strength [2], cladding coating to increase the high temperature oxidation resistance [3, 4], FeCrAl alloy [5, 6] and SiC/SiCf material [7] to increase the oxidation resistance and strength at high temperature. To commercialize the ATF cladding concepts, various factors are considered, such as safety under normal and accident conditions, economy for the fuel cycle, and developing development challenges, and schedule. From the proposed concepts, it is known that the cladding coating, FeCrAl alloy, and Zr-Mo claddings are considered as a near/mid-term application, whereas the SiC material is considered as a long-term application. Among them, the benefit of cladding coating on Zr-based alloys is the fuel cycle economy regarding the manufacturing, neutron cross section, and high tritium permeation characteristics. However, the challenge of cladding coating on Zr-based alloys is the lower oxidation resistance and mechanical strength at high-temperature than other concepts. Another important point is the adhesion property between the Zr-based alloy and coating materials.

As an improved coating technology compared to a previous study [8], a 3D laser coating technology supplied with Cr powders is considered to make a coated cladding because it is possible to make a coated layer on the tubular cladding surface by controlling the 3-diminational axis. We are systematically studying the laser beam power, inert gas flow, cooling of the cladding tube, and powder control as key points to develop 3D laser coating technology. After Cr-coating on the Zr-based cladding, ring compression and ring tensile tests were performed to evaluate the adhesion property between a coated layer and Zr-based alloy tube at room temperature (RT), and a high-temperature oxidation test was conducted to evaluate the oxidation behavior at 1200^{o}C of the coated tube samples.

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2. Methods and Results

The coating equipment is basically consists of a nozzle, lens assembly, powder supplier, and laser source parts. As a laser source, a continuous wave (CW) diode laser with a maximum power of 300 W (PF-1500F model; HBL Co.) was used to coat Cr powder on a Zircaloy-4 plate and cladding tube. The quality (laser beam size, density, and shape) of the laser light was controlled by a lens assembly. In the 3D laser coating, the key technology is a coating nozzle and powder supplier, because the uniform coated layer and adhesion property can be determined by these two factors. The 3D laser coating parameters such as the laser power, specimen velocity, powder injection, and gas flow were systematically studied on the plate type substrate [8]. Finally, the applied power for the LBS treatment ranged from 80 to 250 W, and the scanning speed ranged from 2 to 15 mm/s. To prevent oxidation, an inert gas (Ar) was continuously bellowed into the melting zone during the 3D laser coating.

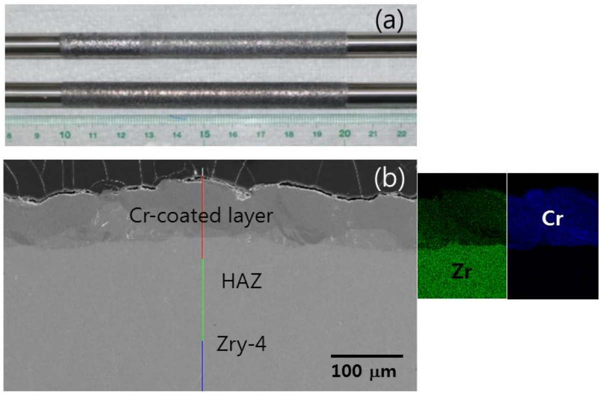

Fig. 1 Surface appearance of Cr-coated Zircaloy-4 cladding (a) and cross-sectional analysis of Cr-coated layer using SEM.

Through a coating parameter optimization, a Cr-coated layer with a 100 mm length can be made on a Zircaloy-4 cladding tube surface without a crack formation, surface oxidation, or deformation to the axial or hoop direction of the cladding tube. The coated area showed a rough surface, because the melted Cr particles were attached to the coated surface during the coating process, as shown in Fig. 1 (a). However, this rough surface can be easily controlled by a grinding using SiC paper. From the cross-sectional observation using SEM, as shown in Fig. 2 (b), it was identified that the Cr layer was well attached on the Zircaloy-4 cladding surface, and the mean thickness of the coated layer was 80 μm.

An adhesion property is a key issue in coating technology, because the application of the surface coating is impossible if the coated layer is spalled or peeled out from the base material. Since the coated layer can be easily damaged by a severe reactor environment during normal operation, and under accident conditions, the adhesion property of the fuel cladding can be considered a very import factor. In general, the limitation of creep deformation of a cladding tube in the normal operation condition was 1% for the hoop direction of tube. From the ring tensile and compression tests for the coated samples, the peeling or spalling phenomenon of the Cr-coated layer attached on the Zircaloy-4 cladding tube was not observed during both ring tests, although the Cr-coated layer was cracked more than the 4 % strain during the ring tensile test.

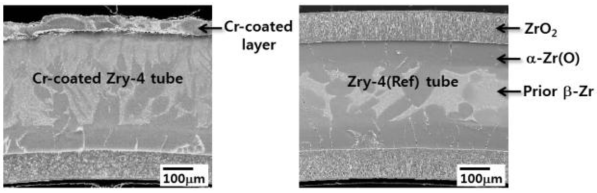

Fig. 2. Cross-sectional SEM observation of the Cr-coated Zircaloy-4 cladding tube and the reference Zircaloy-4 cladding tube after a high-temperature oxidation test at 1200°C for 2000 s in a steam environment.

Fig. 2 shows the cross-sectional SEM observation of the Cr-coated Zircaloy-4 cladding using 3D laser coating technology and the reference Zircaloy-4 cladding after the high-temperature oxidation test at 1200oC for 2000 s in a steam environment. The oxidation level was determined using an SEM image and EDS analysis result. It was clearly identified that the Cr-coated layer on a Zircaloy-4 tube was maintained without spallation or severe oxidation, and the thickness of the oxide layer was less than 4 μm. However, the thickness of the ZrO2 layer formed on the uncoated Zircaloy-4 cladding tube surface was about 113 μm.

3. Conclusions

A 3D laser coating method supplied with Cr powders was developed to decrease the high-temperature oxidation rate in a steam environment through a systematic study for various coating parameters, and a Cr-coated Zircaloy-4 cladding tube of 100 mm in length to the axial direction can be successfully manufactured. From the ring tensile and compression tests for the coated samples, the peeling or spalling phenomenon of the Cr-coated layer attached on the Zircaloy-4 cladding tube was not observed during both ring tests, although the Cr-coated layer was cracked more than the 4 % strain during the ring tensile test. The Cr-coated layer showed a good oxidation resistance without severe damage such as peeling and spalling after the high-temperature oxidation test at 1200°C for 2000 sec.

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