Development Status of Accident Tolerant Fuel Cladding for LWRs

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1. Introduction

A top priority in the nuclear industry is dealing with the safe, reliable, and economic operation of nuclear power plants for a long period of time. After the March 2011 events at Fukushima, enhancing the accident tolerance of LWRs has become a hot issue regarding the fuel development. From the experience of the Fukushima accident, hydrogen explosions and the release of radionuclides can have a serious impact on the public. Hydrogen explosions and the release of radionuclides are caused by severe damage of current nuclear fuels, which are composed of fuel pellets and fuel cladding, during an accident. To reduce the damage to the public, the fuels have to enhance their integrity under an accident environment. Enhanced accident tolerance fuels (ATFs) can tolerate a loss of active cooling in the reactor core for a considerably longer time period during design-basis and beyond design-basis events while maintaining or improving the fuel performance during normal operations as well as operational transients, in comparison with the current UO2-Zr alloy system used in the LWR [1].

Regarding the ATF cladding development, various ATF cladding concepts have been proposed and developed in many research parties [2-8]. The major target of ATF cladding concepts is how to enhance the oxidation resistance and mechanical strength when compared to the current Zr-based alloys under accident conditions [2-7]. Thus, at the present time, the candidate ATF cladding concepts can be summarized as coated Mo-Zr cladding [3], cladding coating [4, 5], iron-based alloy cladding [6], and SiC_f/SiC cladding [7]. In the ATF cladding concept design, cladding must consider various factors such as the safety, economics, fuel cycle, technological challenge, and development schedule. Thus, coated Zr alloy, iron-based alloy, and coated Mo-Zr claddings are being developed as a mid-term application, whereas SiC cladding is considered for long-term application. At KAERI, the surface modified-Zr cladding concept was preferentially selected as an ATF cladding after the consideration of various performances under accident and normal conditions [9]. The surface modified-Zr cladding concepts consist of two technologies of surface coating and partial oxide dispersion strengthened (ODS) treatment shown in Fig. 1. Thus, surface modified-Zr alloys are considered as an ATF cladding as a way to decrease the hydrogen generation by coating as well as to decrease the ballooning and rupture opening by ODS during accident conditions. The detailed technical results are introduced in this work.

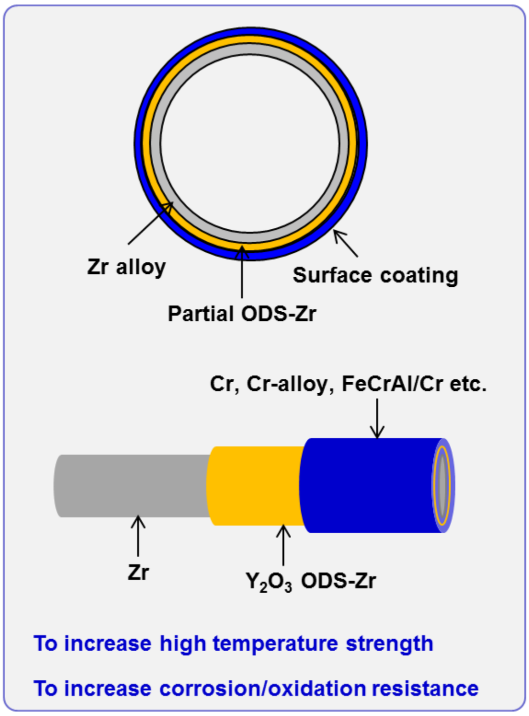

Fig. 1. Schematic illustration of surface modified Zr alloy concept for ATF cladding [10].

2. Methods and Results

Fuel cladding provides the initial barrier to the release of fission products in nuclear fuel, and cannot considerably impact the fuel cycles. Fundamentally, the ATF cladding concept has to meet the current LWR design constraints, if it is to be applied to the current LWRs without a severe design change for near term application. Thus, the candidate concepts will be considered as the cladding criteria such as the compatibility, performance, economy, safety (DBA and BDBA), and fuel cycle in LWRs. It is known that the scientific and engineering challenges associated with nuclear technology result in a long, complicated fuel cladding qualification process. The development progress of new fuel concepts will consist of the design, manufacturing, testing, and evaluation. In addition, these steps will be repeated to obtain the optimum performance of the fuel cladding in the R&D strategy.

The major benefit of the surface modified Zr alloy concept is the economics because the commercial Zr-based alloy and manufacturing facility can be continuously operated. However, the challenge of the surface modified Zr alloy concept is how to obtain the good adhesion property between Zr based alloy and the coating materials. Fig. 1 shows a schematic illustration of the developed coating technologies for the surface modified Zr alloy concept. Here, the functionally graded materials (FGM) can be characterized by the variation in composition and structure gradually of two materials.

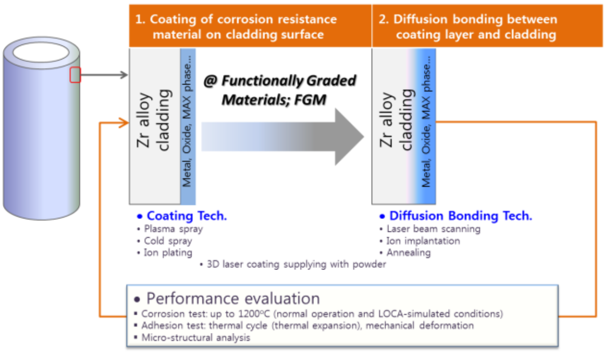

Fig. 2. Schematic illustration of the coating technology for surface modified Zr alloy concept.

After consideration of the various coating technologies, it was concluded that diffusion bonding as a key technology can be produced by an additional treatment using laser beam scanning, ion implantation, or annealing after the general coating such as plasma spray, cold spray, or ion plating. In the case of a 3D laser coating supply with powder, the diffusion bonding can be produced by single process without the combined processes of coating technology and diffusion bonding technology. However, the coating technology is considerably affected by the coating materials such as the alloy composition, structure, and shape. For the basic screening of the coating adhesion, corrosion/oxidation, thermal cycle, and mechanical tests were performed. Therefore, arc ion plating and 3D laser coating methods were selected for surface coating on Zr alloys.

The performance of enhanced ATF cladding concepts is fundamentally focused on the corrosion behavior and mechanical strength under normal operation, as well as the oxidation behavior and ballooning/rupture behavior during accident conditions. Thus, the corrosion/oxidation resistance and strength at high-temperature have to improve more than the current Zr alloys. In detail, the corrosion/oxidation resistance during normal operation and under accident conditions can be increased by the surface coating method, and the high-temperature strength of the cladding can be increased by the partial ODS method as shown in Fig. 1.

3. Results and Discussion

Through a coating parameter optimization, a Cr-alloy coated layer with a 200 mm length can be made on a Zircaloy-4 cladding tube surface without a crack formation, surface oxidation, or deformation of the axial or hoop direction of the cladding tube. The coated area showed a rough surface, because the melted Cr-alloy particles were attached to the coated surface during the coating process as shown in Fig. 3. At the present time, the 3D laser coating is limited by the power supply, because the manufacturing of the new alloy powder with a very high melting point is difficult. FeCrAl alloy or pure Cr coating is possible using the 3D laser coating method. It was identified that a pure Cr layer or multiple Cr/FeCrAl layers were well produced on the Zircaloy-4 cladding surface. Here, the Cr layer in the multiple Cr/FeCrAl layers was deposited using the arc ion plating method.

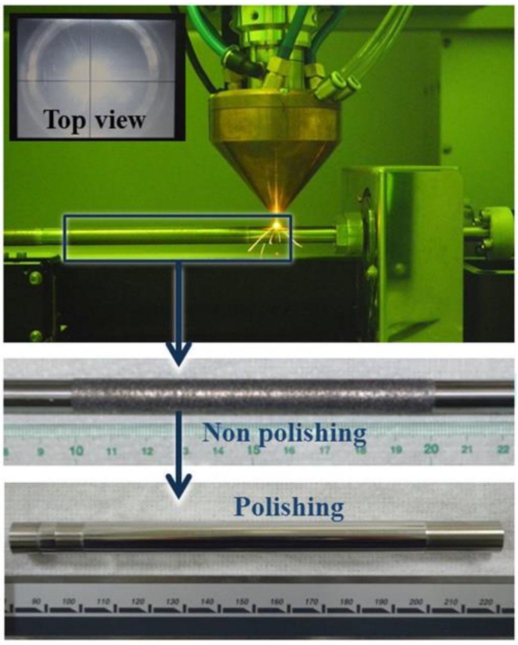

Fig. 3. 3D laser coating process and coated Zircaloy-4 cladding sample.

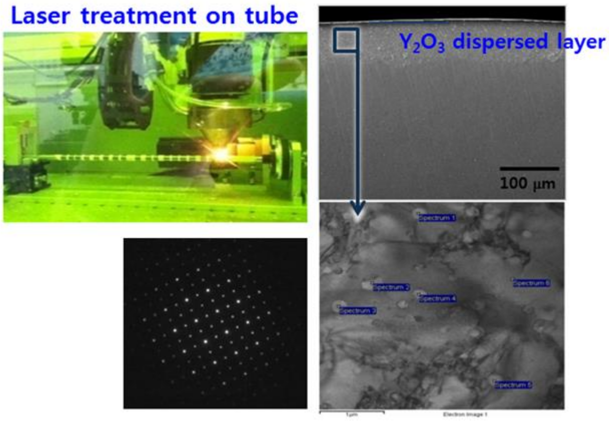

Fig. 4. LBS process on Zircaloy-4 cladding and cross-sectional observation of the microstructure.

Fig. 4 shows a laser beam scanning process (LBS) on Zircaloy-4 cladding to make the partial ODS layer and cross-sectional observation of the microstructure. The thickness of the average ODS treated layer of the Zircaloy-4 cladding tube was about 100 µm, and reached about 17 % of the initial Zircaloy-4 cladding tube thickness. It was observed that the Y2O3 particles, which were identified through a SEM-EDS point analysis and TEM analysis, were uniformly distributed in the reaction area.

4. Conclusions

Surface modified Zr cladding as a new concept was suggested to apply an enhanced ATF cladding. The key technologies of this new concept consisted of partial ODS treatment and surface coating. The aim of the partial ODS treatment is to increase the high-temperature strength to suppress the ballooning/rupture behavior of fuel cladding during an accident event. The target of the surface coating is to increase the corrosion resistance during normal operation and increase the oxidation resistance during an accident event. The partial ODS treatment of Zircaloy-4 cladding can be produced using a laser beam scanning method with Y2O3 powder, and the surface Cr-alloy and Cr/FeCrAl coating on Zircaloy-4 cladding can be obtained after the development of 3D laser coating and arc ion plating technologies. From this result, it is known that each technology for increasing the corrosion/oxidation resistance as well as the mechanical strength shows a good property to make the ATF cladding.

Acknowledgment

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