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Mechanical Property and Oxidation Behavior of ATF cladding developed in KAERI

Hyun-Gil Kim*, Il-Hyun Kim, Yang-Il Jung, Dong-Jun Park, Jung-Hwan Park, Jeong-Yong Park, Yang-Hyun Koo
LWR Fuel Technology Division, KAERI, 989-111 Daedeok-daero, Yuseong-gu, Daejeon, 305-353, Republic of Korea
Corresponding author: hgkim@kaeri.re.kr

1. Introduction

A top priority in nuclear industry is focused on the safe, reliable and economic operation of nuclear power reactor for a long time. However, enhancing the accident tolerance of LWRs became a hot topic regarding the fuel development after the March 2011 events at Fukushima. To cope with the new situation, the Congress in USA directed DOE-NE to give "priority to developing enhanced fuel and cladding for light water reactors to improve the safety in the event of accident in the event of accident in the reactor or spent fuel pools [1]." In comparison with the standard UO_2-Zr alloy system which is currently used in the LWRs, enhanced accident tolerance fuels (ATF) can tolerate loss of active cooling in reactor core for a considerably longer time period during design-basis and beyond design-basis event while maintaining or improving the fuel performance during normal operations and operational transients [1].

At the present time various ATF concepts have been proposed and developing in many countries [2-5]. The ATF concepts with potentially improved accident performance can be summarized to the coating cladding [2], Mo-Zr cladding [3], FeCrAl cladding [4], and SiC_f/SiC cladding [5]. Regarding the cladding performance, ATF cladding concepts will be evaluated with respect to the accident scenarios and normal operations of LWRs as well as to the fuel cladding fabrication. In KAERI, the coated cladding concept was preferentially selected as an ATF cladding after the consideration of various performances in accident and normal conditions. The mechanical property and oxidation behavior at high-temperature of coated cladding concept are introduced in this study.

2. Methods and Results

2.1 Consideration of ATF cladding concepts

Fuel cladding provides the initial barrier to release of fission products in nuclear fuel, and cannot considerably impacts on the fuel cycles. Fundamentally, ATF cladding concept has to meet the current LWR design constraints, if that will be applied to the current LWRs. Thus, the candidate concepts will be considered to the cladding criteria such as compatibility, performance, economy, safety (DBA and BDBA), and fuel cycle in LWRs as shown in Fig. 1.

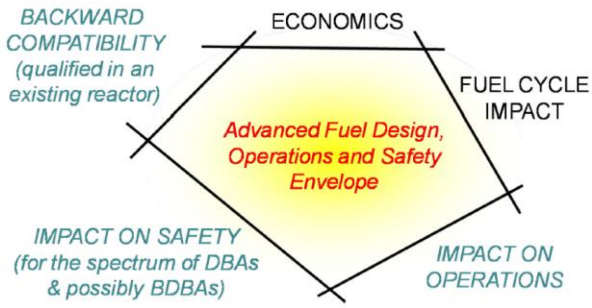

Fig. 1. Constraints on new fuel designs [6].

It is known that the scientific and engineering challenges associated the nuclear technology result in a long, complicated fuel cladding qualification process. The development progress of new fuel concepts will be consisted of design, manufacturing, testing, and evaluating. And these steps will be repeated to obtain an optimum performance of cladding in the R&D strategy. The performance of enhanced ATF cladding concepts for safety is fundamentally focused on the corrosion behavior and mechanical strength in a normal operation, as well as the oxidation behavior and a ballooning/rupture behavior during the accident conditions. Thus, the corrosion/oxidation resistance and strength at high-temperature have to improve more than the current Zr alloys. The surface modified Zr cladding concept has been developing as a one of the candidates for ATF cladding because the corrosion/oxidation resistance and the high temperature strength of Zr alloy can be improved by using surface modified technology. This concept contains two technologies based on the material-based approaches. In detail, the corrosion/oxidation resistance in a normal operation and accident conditions can be increased by the surface coating method, and the high-temperature strength of cladding can be increased by the partial ODS method. Since this surface modified concept is developed based on the current Zr alloy cladding, the commercialization for fuel cladding will be easy when compared to other concepts. However, it is recognized that the stability at high temperature and adhesion property between coating layer and Zr alloy substrate are considered to the weak point of the coating cladding concepts. Thus, the adhesion property of coated cladding is basically evaluated.

2.2 Development of surface modified Zr alloy concept

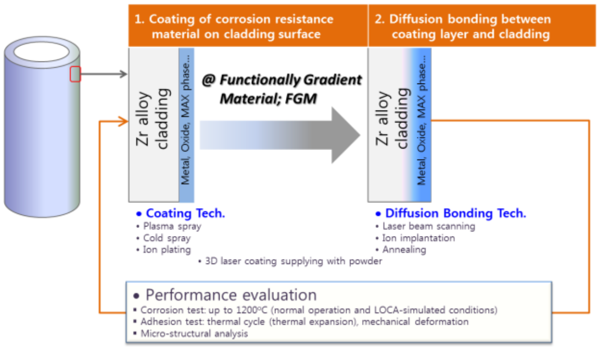

Fig. 2. Schematic diagram of coating technology development in KAERI

Fig. 2 shows an example for developing the coating cladding to improve the adhesion property between coated layer and Zr substrate. In this R&D progress, the key point is to make a FGM (functionally gradient material) between coating layer and Zr cladding by using the advanced coating technologies. As a coating method, plasma spray, cold spray, ion plating or 3D laser coating is used to make a coated layer on the Zr alloy cladding surface. And laser beam scanning, ion implantation, or annealing process can be used to make a diffusion bonding at the interface.

One of the important factors of coated cladding concept is coating materials, because the cladding properties are determined by the material property. It is known that SiC material can be dissolved in the normal condition in LWRs, although that material have the excellent oxidation resistance at high temperature steam condition when compared to the Zr alloys. Thus, it is confirmed that the coating materials have a good corrosion and oxidation resistance ranged from the normal operation condition of 300°C in pressured-water to the accident condition of 1200°C in steam. To developed the coating materials, various parameter studies are performed after considering the corrosion/oxidation mechanism, mechanical property, physical property, and neutron effect among various materials. From the parameter study using model alloys, the Cr-based alloy can be developed as a coating material. This alloy shows a superior oxidation/corrosion resistance in water and steam conditions to the commercial Zr alloys.

After manufacturing the coated tube samples using 3D laser coating and arc ion plating combined with vacuum annealing, the mechanical property and the oxidation/corrosion behavior are evaluated to check the performance of the coated cladding. Mechanical property is evaluated by using the ring-type test samples of cladding because the cladding deformation during the normal and accident conditions is progressed to the hoop direction of the cladding tube. From the ring compression and tensile tests at room temperature, the adhesion property of the coated Zr cladding was reasonable to apply a fuel cladding, since the peeling or spalling phenomenon of the coated Zr cladding was not observed. The oxidation test of coated samples was performed in a 1200°C steam environment, and the commercial Zr alloy as a reference cladding was tested in a same condition. The oxidation resistance of the coated cladding is considerably improved when compared to the commercial Zr alloy cladding. The coated layer was maintained without any physical damage such as cracking, spalling, and severe interactions between coated layer and Zr alloy cladding after the high-temperature oxidation test.

3. Conclusions

After consideration of the fuel cladding development strategy, the coated cladding concept for applying the ATF cladding should be suggested. To realize the coating cladding, coating material (Cr-based alloy) as well as coating technology (3D laser coating and arc ion plating combined with vacuum annealing) can be developed to meet the fuel cladding criteria. The coated Zr cladding can be produced after the optimization of coating technologies. The coated cladding sample showed the good oxidation/corrosion and adhesion properties without the spalling and/or severe interaction with the Zr alloy cladding from the various tests. Thus, it is known that the mechanical property and oxidation behavior of coated cladding concept developed in KAERI is reasonable for applying the ATF cladding in LWRs.

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