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Development of Enhanced Accident Tolerant LWR Fuel Cladding

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1. Introduction

The safe, reliable and economic operation of nuclear power reactor has always been a top priority in nuclear industry. After the March 2011 events at Fukushima enhancing the accident tolerance of LWRs became a serious topic regarding the fuel development. In USA, the Congress directed DOE-NE to give "priority to developing enhanced fuel and cladding for light water reactors to improve safety 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].

As the ATF cladding concepts, coating cladding, Mo-Zr cladding, FeCrAl cladding, and SiC/SiC_f cladding have being developed in many countries [2]. Regarding the cladding performance, new fuel cladding concepts will be evaluated with respect to the accident scenarios and specific plant designs for LWRs and fuel cladding fabrication facilities. After the consideration of various performances in accident and normal conditions, the coating cladding concept was selected to apply an ATF cladding in this study. However, the coating concept on Zr-based alloy cladding has to improve the mechanical strength at high-temperature, although the oxidation resistance of coating cladding is more improve than Zr-based alloy at normal and accident conditions [2]. The mechanical strength of cladding material at high-temperature is very important to suppress the ballooning/rupture behavior of fuel cladding. The reactor core coolability is considerably affected by the ballooning behavior of fuel cladding, and the release of radioactivity to the environment is directly affected by the fuel cladding rupture during the accident. Thus, the corrosion/oxidation resistance as well as deformation resistance at normal and accident conditions will be required in the ATF cladding concepts.

2. Methods and Results

To obtain the oxidation/corrosion resistance and mechanical strength, the surface modified cladding concept was developed to apply an enhanced accident tolerant fuel cladding. Fig. 1 shows the surface modified cladding concept. This concept contains two technologies of outer surface coating and partial oxide dispersion strengthened (ODS) structure at the intermediated region between outer coated layer and Zr alloy tube.

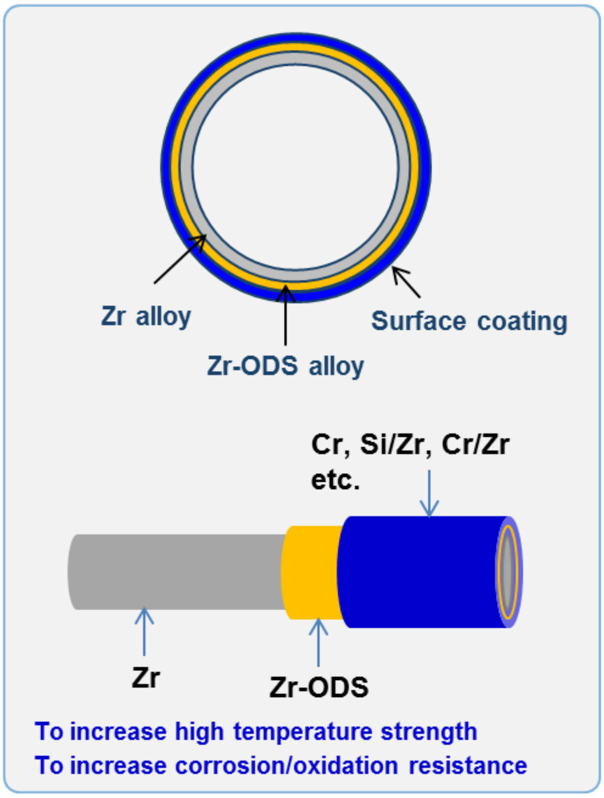

Fig. 1. Schematic drawing of the surface modified cladding concept to apply enhanced accident tolerance fuel cladding.

2.1 Partial ODS Treatment

A Zircaloy-4 cladding was used in this study because this alloy has been used as a reference cladding material for a long time. To make a partial ODS layer laser beam scanning method was used after detailed parameter study such as laser energy, scan speed, inert gas flow, and Y_2O_3 powder control. Before the LBS, the substrates were cleaned by alcohol to remove stains or contamination on the surface and then dried. The mean size of the Y_2O_3 powders, which were supplied by Richest Group Ltd., was less than 10 μm. These powders were spread onto the Zircaloy-4 cladding tube in a suspended state with alcohol, and then dried. After drying, the thickness of the Y_2O_3 powder layer was about 25 μm, which was measured using an eddy current tester (ECT). The surface of the Y_2O_3 spread Zircaloy-4 sheet was scanned by a continuous wave (CW) diode laser with a maximum power of 250 W. The microstructure and composition of an ODS alloying layer for a cross-sectional view have been determined using an optical microscope (OM), SEM with an energy dispersive spectrometer (EDS), and a high resolution (HR)-TEM analysis.

A detailed characterization of the oxide dispersion microstructure prepared using the LBS method is very important because it is the first time to make an ODS microstructure of a Zircaloy-4 cladding tube. The thickness of an average ODS treated layer of the Zircaloy-4 cladding tube was about 100 μm, and this thickness reached about 17 % of the initial Zircaloy-4 cladding tube thickness. It was observed that the Y_2O_3 particles, which were identified by a SEM-EDS point analysis and a TEM analysis, were uniformly distributed in the reaction area.

2.2 Surface Cr-alloy Coating

3D laser coating method was developed to make a surface coating layer on Zircaloy-4 cladding. The laser equipment is basically consisted of a nozzle, powder supplier, and laser source parts. As a laser source, a continuous wave (CW) diode laser with a maximum power of 300 W was used to coat Cr-alloy 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 tube type substrate [2]. 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.

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 to 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. It was identified that the Cr-alloy layer was well attached on the Zircaloy-4 cladding surface, and the mean thickness of the coated layer was 80 μm form the cross-sectional analysis of microstructure. 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. Thus ring tensile and compression test methods were used to evaluate the adhesion property between coating layer and substrate. The peeling or spalling phenomenon of the Cr-alloy coated layer attached on the Zircaloy-4 cladding tube was not observed during both ring tests

3. Conclusions

A surface modified cladding as a new concept is suggested to apply an enhanced accident tolerance fuel cladding. The key technologies of new concept were consisted of the 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 accident event. The target of the surface coating is to increase the corrosion resistance during normal operation condition and to increase the oxidation resistance during accident event. The partial ODS treatment of Zircaloy-4 cladding can be produced by using the laser beam scanning method with Y_2O_3 powder, and the surface Cr-alloy coating on Zircaloy-4 cladding can be obtained after development of the 3D laser coating technology. 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. In next time, the combined technologies between the partial ODS treatment and the 3D laser coating will be developed.

REFERENCES

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