Formation of an Oxide-Dispersion-Strengthened Layer on Zirconium-based Fuel Cladding Tubes Manufactured by KEPCO NF

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1. Introduction

Accident tolerant fuel (ATF) cladding is being developed globally after the Fukushima accident with the demands for the nuclear fuel having higher safety at normal operation conditions as well as even in a severe accident conditions. Korea Atomic Energy Research Institute (KAERI) is one of the leading organizations for developing ATF claddings [1,2]. Various ATF concepts have been developed via a national R&D project with the grant of Ministry of Science and ICT from 2012. Recently, a new project was launched to develop the irradiation test rod using ATF pellets and cladding in collaboration with research institute, nuclear fuel vendor, and universities under the funding of Ministry of Trade, Industry and Energy. This paper explains one of concepts being developed in the latter project, i.e., zirconium alloy based cladding consisting of oxide dispersion strengthened (ODS) layer and surface coating.

The ODS treatment was proposed to increase the strength of the Zr-based alloy up to high temperatures [2-6]. High-power laser beam was exposed on the zirconium surface previously coated by oxides (typically Y_2O_3). The dispersed oxide layer was formed by the penetration of oxide particles into Zr alloys. According to our previous investigations [3-6], the tensile strength of Zircaloy-4 was increased by up to 20% with the formation of a thin dispersed oxide layer with a thickness less than 10% of that of the Zircaloy-4 substrate. In this paper, the ODS treatment was performed using developing fuel claddings by the KEPCO NF, e.g., KNF-M and HANA-6. The effect of process conditions on the formation of ODS layer was investigated.

2. Methods and Results

2.1. Experimental for ODS Treatment

Three kinds of Zr-based tubes (Zircaloy-4, KNF-M, and HANA-6) with an outer diameter of 9.5 mm and a wall thickness of 0.57 mm were used. The tubes were cut in length of 500 mm and cleaned with alcohol and acetone. Y_2O_3 was coated on the cleaned Zircaloy-4 tubes by a dip-coating method. To prepare the dip solution, Y_2O_3 powder was dissolved in ethyl-alcohol at a solute content of 10%. Then, polyvinyl alcohol (PVA) was added as a binder. The PVA was supplied as a water-based solution. The amount of PVA was 1 wt.% of the Y_2O_3 content. The solution was mixed for 24 h using zirconia balls. Zirconium tubes were immersed in the solution and then slowly drawn out to form a coating layer. The wet-coated tubes were dried in a vacuum oven at 50°C for 20 min. The Y_2O_3-coated cladding tubes were scanned by a laser.

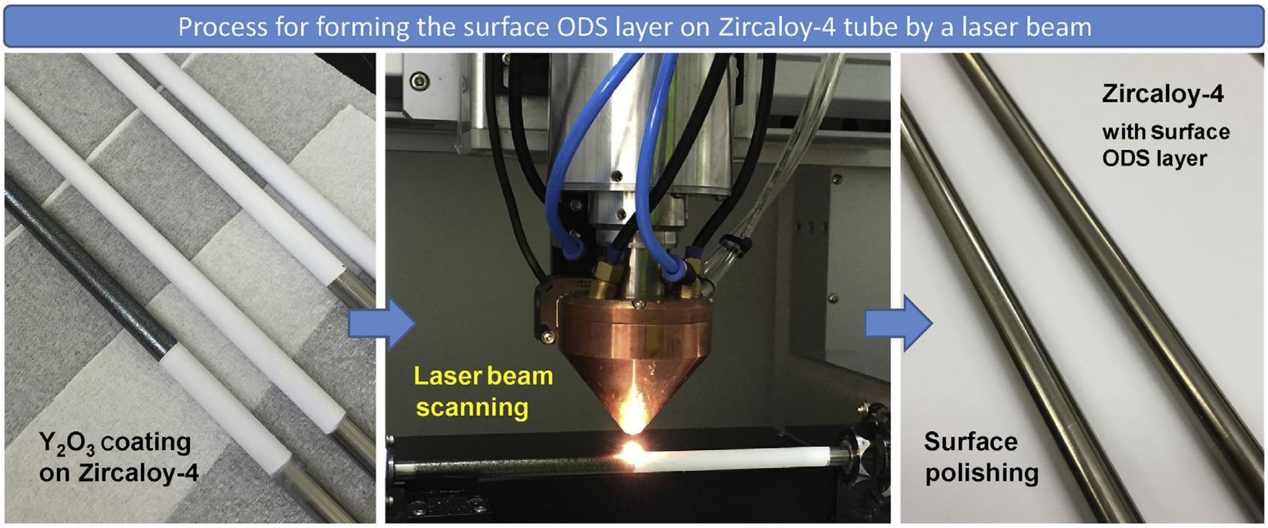

Fig. 1. Fabrication process for forming a surface ODS layer on Zircaloy-4 tube using a laser beam [6].

The laser was a continuous wave diode laser with the beam diameter of 230 μm. The ODS layer was formed at a laser beam power of 120–180 W and scan speed of 10 mm/s. The laser beam was scanned continuously along the circumferential direction with an overlap distance of 0.2–0.4 mm. To prevent oxidation and blow off the PVA binder, Ar gas was continuously blown on the samples' surfaces during laser processing. Cooling water was supplied to the inside of the tubes to release the induced heat. The representative process was presented in Fig. 1 [6].

2.2. Microstructures

Fig. 2 shows the cross-sectional microstructures of the ODS treated Zircaloy-4 samples. The ODS layer was observed at the surface with dark contrasts. The microstructure along the axial direction revealed the formation of a dispersed oxide layer 50–140 μm in thickness in the surface region. The helical laser beam scans with a fixed offset distance of 0.4 mm produced the wavy interface. The thermal energy induced by a laser beam is known to form a heat-affected zone (HAZ); however, the formed HAZ is not distinguishable from the Zr matrix in these micrographs.

Fig. 3 shows the cross-sectional microstructures of the ODS treated KNF-M and HANA-6 samples. In the case of Zircaloy-4, the as-received tubes showed a cold-worked and stress-relieved microstructure. In the case of KNF-M and HANA-6, recrystallized microstructures were observed in the as-received tubes. For the treatment shown in Fig. 3, laser beam was changed to have large beam size of 1 mm due to equipment situation. Because the induced thermal energy was hardly dissipated, the HAZ was enlarged as compared to that of Zircaloy-4. Note that the direct comparison is difficult. The processing under same beam conditions is in progress. One question, however, is that the ODS layer is not distinct from the microstructures. Detailed analysis will be made in the future.

3. Conclusions

Surface treatment was performed by a laser beam to form a dispersed oxide layer in Zr-based alloys. Laser beam scanning of a tube coated with yttrium oxide (Y_2O_3) resulted in the formation of a dispersed oxide layer in the tube's surface region. It is the early stages of the experiment using alloys developed by KEPCO NF. Continuous research will be done to form the optimal ODS layer in these alloy tubes.

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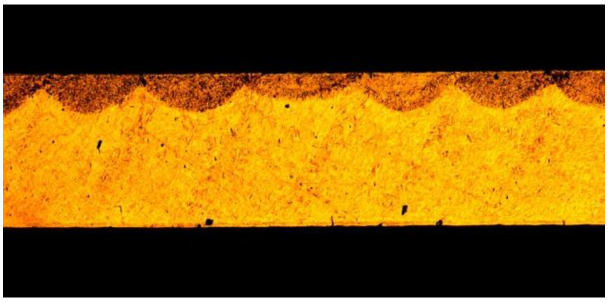

Fig. 2. Cross-sectional microstructures of ODS Zircaloy-4 samples showing the ODS layer formed at the surface.

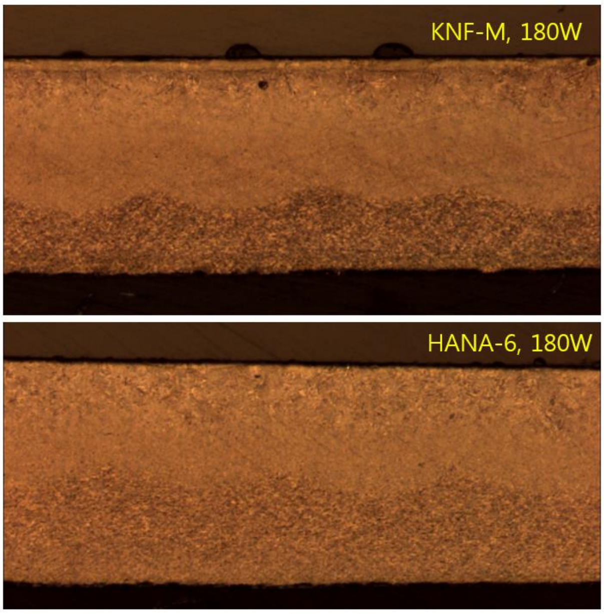

Fig. 3. Cross-sectional microstructures of ODS treated KNF-M and HANA-6 samples.

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