Formation of Lamellar Structured Oxide Dispersion Strengthening Layers in Zircaloy-4

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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]. One concept is to form an oxidation-resistant layer on Zr cladding surface. The other is to increase high-temperature mechanical strength of Zr tube.

The oxide dispersion strengthened (ODS) zirconium was proposed to increase the strength of the Zr-based alloy up to high temperatures [2,3]. The ODS treatment on the Zr surface layer was successfully performed using a laser beam scanning (LBS) process, as shown in Fig. 1 [3]. High-power laser beam was exposed on the zirconium surface previously coated by oxides such as Y_2O_3 and CeO_2. The dispersed oxide layer was formed by the penetration of oxide particles into Zr alloys.

According to our previous investigations [3-5], 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. However, the tensile elongation of the samples decreased drastically. The brittle fracture was a major concern in development of the ODS Zircaloy-4. In this study, a lamellar structure of ODS layer was formed to increase ductility of the ODS Zircaloy-4.

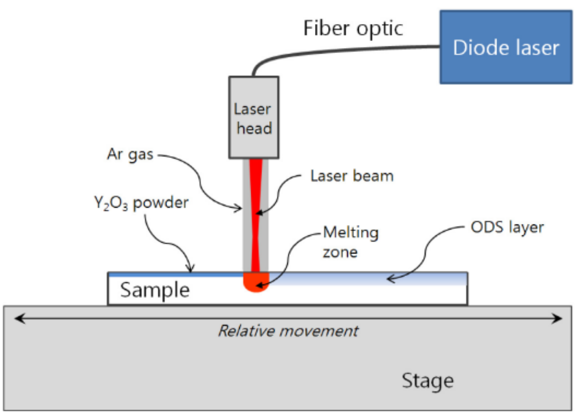

Fig. 1. Schematic illustration of ODS treatment using a laser beam scanning [3].

2. Methods and Results

A Zircaloy-4 (Zr-1.5Sn-0.2Fe-0.1Cr) alloy sheet with 2 mm in thickness was used as a substrate. Oxide powder of Y_2O_3 (99.9%, 1 μm, Alfa Aesar, USA) was purchased, and coated on Zircaloy-4 sheet with the thickness of 10–55 μm. Oxide coating was prepared using a water-based slurry containing a polyvinyl alcohol (3 wt% to oxide powders) as a binder. The slurry was coated on Zircaloy-4 plate by a doctor blade, and dried in an oven at 80°C for 30 min. The coated Zircaloy-4 samples were laser beam scanned by a continuous wave diode laser with a maximum powder of 250 W (PF-1500F, HBL Co, Korea). To prevent oxidation during the LBS, Ar gas was continuously blew onto the melting zone through a laser nozzle. Schematic illustration of LBS was shown in Fig. 1. Beam diameter was 230 μm. Hatching distance and scan speed were set as 0.4 mm and 10 mm/s, respectively. The laser beam scanned Zircaloy-4 sheets were stacked to form a multi-layered structure. To consolidate the stacked sheets, hot isostatic pressing (HIP) was conducted. Then, HIP samples were hot-rolled and cold-rolled to become plate samples. The mechanical strength of the samples were evaluated via the tensile test and fatigue test.

3. Results and Discussion

Multiple ODS layers were formed after HIP joining of surface ODS treated Zircaloy-4 samples. Six surface ODS treated samples were stacked and HIP bonded. For each sample, an ODS layer of ~100 μm thick was formed on Zircaloy-4 substrate. HIP was performed at 950°C for 2 h under 100 MPa. After decanning, the thickness of the bonded block was 11 mm. Hot-rolling was conducted at 500°C for eight times with an 1 mm reduction magnitude. The thickness of the sample after hot-rolling was 3.61 mm. Then, cold-rolling was conducted with a 0.3 mm reduction magnitude to become a sheet sample with 2.2 mm in thickness. The cross-sectional microstructure of the final product was shown in Fig. 2. ODS treated layers were observed periodically with dark contrasts. In addition, cold-worked microstructures were observed in the Zircaloy-4 matrix. The thickness of the ODS layers and Zircaloy-4 were 16–37 μm and 410 μm, respectively. The volume fraction of ODS treated layer was less than 10%.

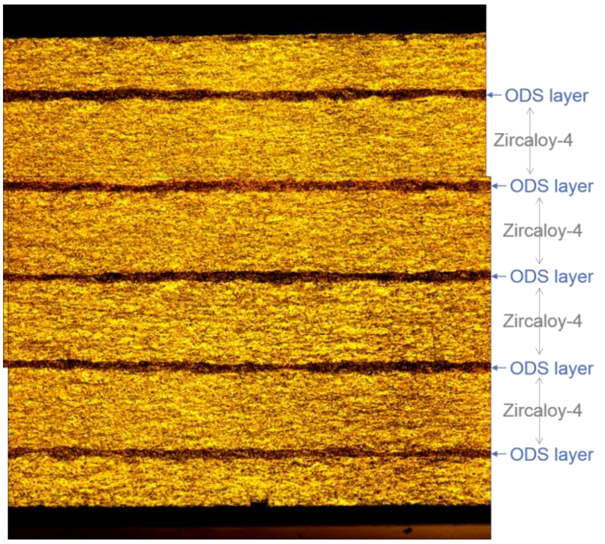

Fig. 2. Cross-sectional microstructures of Y_2O_3-dispersed Zircaloy-4 samples with multi-layers of oxide dispersion strengthened layer.

Fig. 3 shows the tensile stress to strain curves for the fabricated samples. For the tensile test, small-sized specimens with the cross-sectional dimensions of 2 mm × 4 mm and gage-length of 6 mm were machined by a wire electro-discharge machining. The tensile test was performed at room temperature (RT) and elevated temperatures of 380℃ and 500℃ at a displacement rate of 1 mm/min. The tensile strength at RT was varied from 480 MPa to 700 MPa depending on their microstructures. The tendency of stress–strain behavior was similar at elevated temperatures. The drastic reduction in elongation was improved in the lamellar structured ODS Zircaloy-4.

4. Conclusions

Lamellar structured ODS Zircaloy-4 was fabricated by joining of surface ODS treated Zircaloy-4 samples. Multilayers of ODS in thickness of 16–37 µm were formed periodically in Zircaloy-4. The mechanical properties were varied depending on the structure of ODS layer. For example, the partial formation of ODS layer with the thickness of 10% to the substrate thickness induced the increase in tensile strength up to about 20% than fresh Zircaloy-4. In addition, reduction in ductility was insignificant as compared to surface ODS samples. However, more detailed investigation is required to correlate the tensile behavior with their microstructures.

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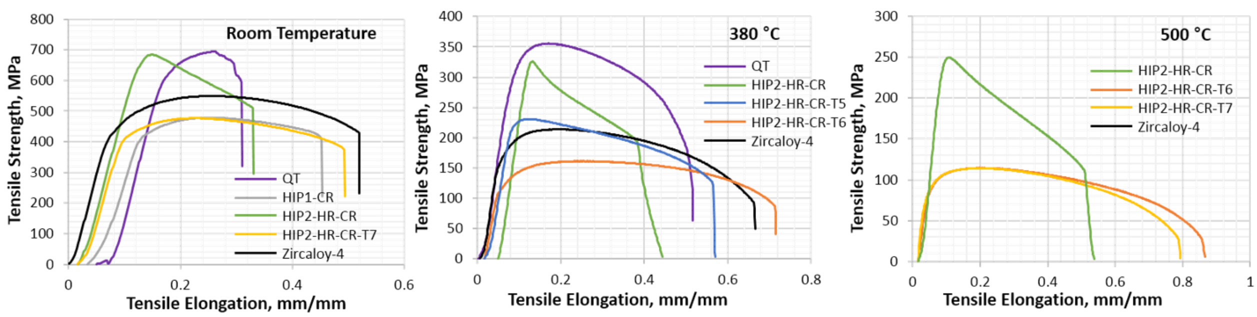

Fig. 3. Tensile stress-strain curves for the lamella ODS Zircaloy-4 samples at room temperature and elevated temperatures of 380℃ and 500℃, respectively.