Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 12-13, 2016

Strengthening of Zircaloy-4 with Oxide Particles by Surface Treatment using Laser Beam

Yang-Il Jung,* Jung-Hwan Park, Dong-Jun Park, Hyun-Gil Kim, Jae-Ho Yang, Yang-Hyun Koo
LWR Fuel Technology Division, KAERI, 989-111 Daedeok-dearo, Yuseong, Daejeon, 34057, Republic of Korea
**Corresponding author: yijung@kaeri.re.kr*

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]. 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]. The ODS treatment on the Zr surface layer was successfully performed using a laser beam scanning (LBS) process, as shown in Fig. 1 [2]. High-power laser beam was exposed on the zirconium surface previously coated by oxides. Various oxides such as Y_2O_3, CeO_2, Gd_2O_3, Er_2O_3 were used for the ODS treatment.

In this study, the effect of strengthening by the ODS treatment was investigated.

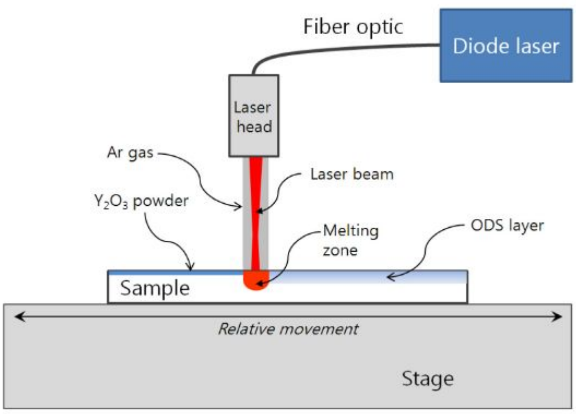

Fig. 1. Schematic illustration of ODS treatment using a laser beam scanning [2].

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 bonder. 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 260 μm. Hatching distances were varied from 0.2 mm to 0.6 mm, whose values are enough to overlap the laser affected zones.

Fig. 2 shows the microstructures of the ODS (Y_2O_3) treated samples. Laser induced ODS alloying layer was observed at the surface with dark contrasts. Below the ODS layer, the heat affected zone was observed about 500 μm in thickness. As the hatching distance was decreased from 0.6 mm to 0.2 mm, the ODS treated layer was overlapped.

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 and 380°C at a displacement rate of 1 mm/min. The thickness of the oxide-dispersed layer was varied 87–192 μm from the Y_2O_3 coating of 10–30 μm in thickness. The tensile strength was increased from 550 MPa to 651–695 MPa; however, the elongation was decreased drastically by 26–34%. On the other hand, the high-temperature strength as well as ductility was obtained at elevated temperature of 380°C. Fig. 4 shows the appearance of specimens after the tensile test at room temperature. Zircaloy-4 revealed ductile fracture surface; however, the brittle fracture of the ODS treated layer was observed. The strength increase by the ODS treatment was caused by the dispersive Y_2O_3 particles and martensite formation on the Zircaloy-4 sheet using an LBS method.

The current technology is quite applicable to increase the high-temperature strength of the Zr alloy while maintaining their bulk microstructures.

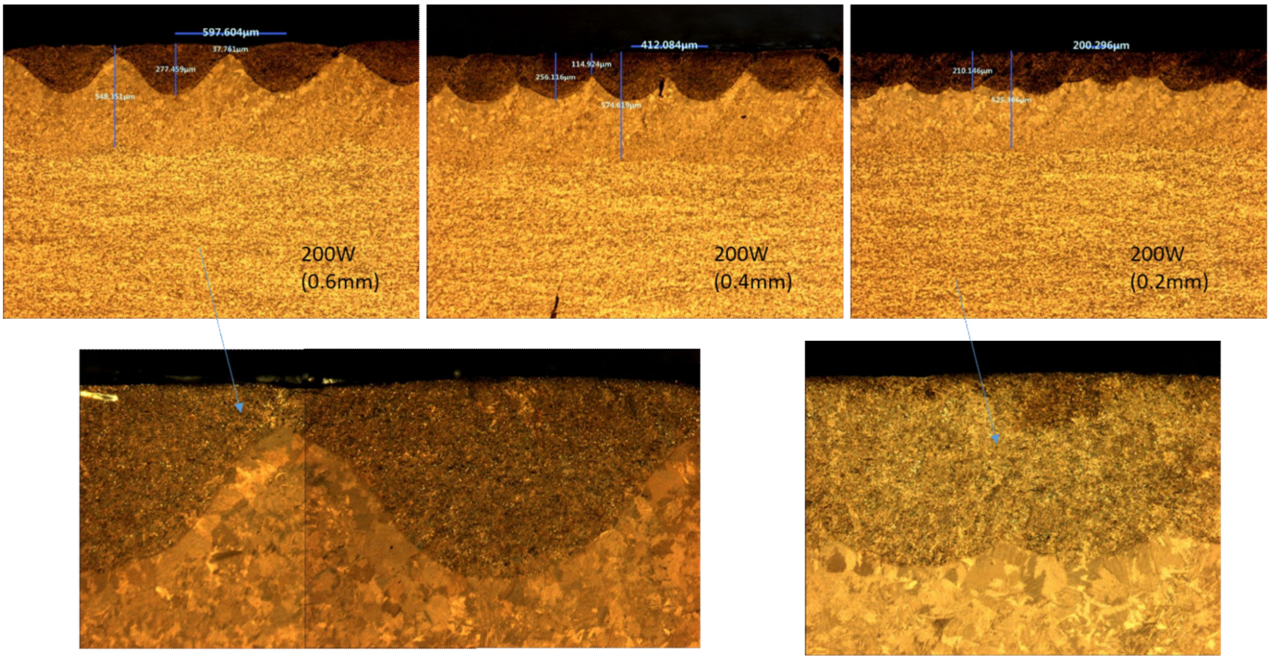

Fig. 2. Cross-sectional microstructures of Y_2O_3-dispersed Zircaloy-4 samples with respect to the hatching distances (0.6, 0.4, 0.2 mm) of the laser beam.

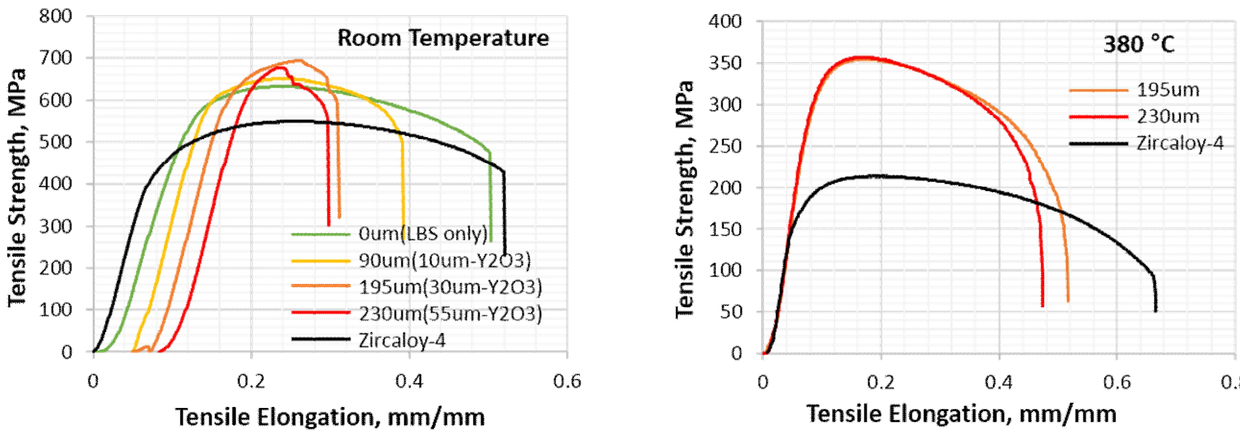

Fig. 3. Tensile stress-strain curves for the ODS(Y_2O_3) Zircaloy-4 samples at room temperature and 380°C, with respect to the thickness of ODS treated layer.

3. Conclusions

Surface modification of Zircaloy-4 used in nuclear fuel cladding tubes was performed using an oxide coating and subsequent laser beam treatment. The oxide particles of Y_2O_3 were dispersed well in the Zr matrix at the surface region. The partial formation of ODS layer with the thickness of 5% to the substrate thickness induced the increase in tensile strength up to about 20% than fresh Zircaloy-4. Especially, the increased ductility was observed at high temperature testing: the strength was increased more than 50% and elongation was decrease less than 30% at 380°C

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government(MSIP) (No. 2012M2A8A5025822)

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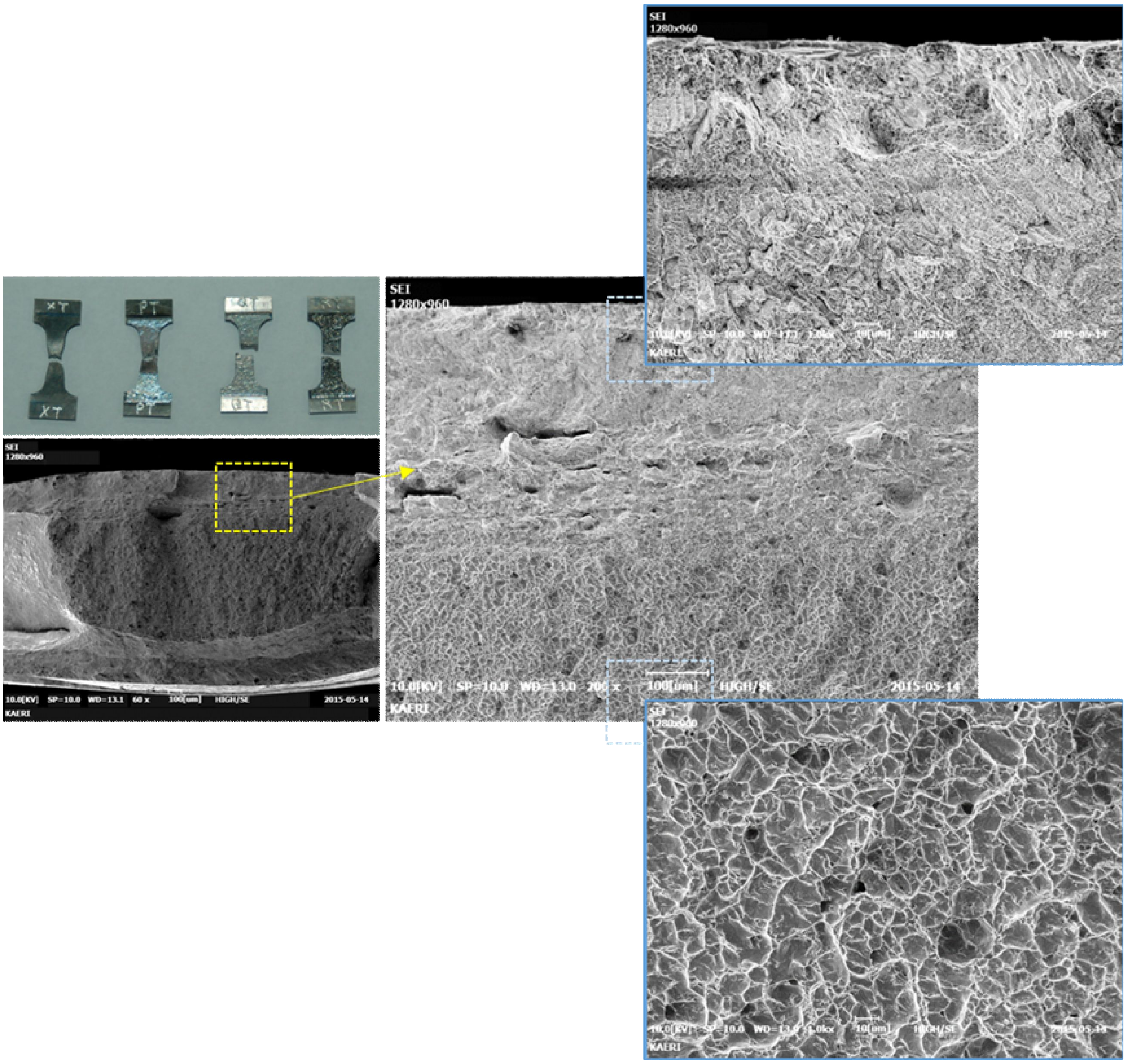

Fig. 4. Appearance of tensile specimens after the test at room temperature for the ODS (Y_2O_3) Zircaloy-4 samples. Microstructures on the fracture surface after the tensile test reveal the brittle fracture at the ODS treated layer and ductile fracture at the middle of the tensile specimen.