Evaluation of Mechanical Strength and Ductility of High burn-up Nuclear Fuel Cladding

Sunki Kim, Jegun Bang, Daeho Kim, Youngmin Kim, Yongsik Yang,
Sangbok Ahn, Dosik Kim, Wanho Oh, Hangseok, Seo
Korea Atomic Energy Research Institute, 150 Dukjin-dong Yusong-gu, Daejeon 305-353, Korea
kimsk@kaeri.re.kr

1. Introduction

During a steady-state operation of light water reactors, the mechanical behavior of the zirconium-based fuel cladding degrades due to a combination of oxidation, hydriding, and radiation damage. In an effort to increase the operating efficiency through the use of longer fuel cycles, and to reduce the volume of waste associated with core reloads, utilities have a strong incentive to increase the average discharge burn-up of the fuel assemblies. Further increases in the operating efficiency of power reactors can also be achieved by increasing the coolant outlet temperature. However, both of these changes in reactor operation enhance the cladding degradation, which may increase the likelihood of cladding failure during design-basis accidents.

One such postulated design-basis accident scenario is the reactivity-initiated accident(RIA) in a pressurized water reactor (PWR) caused by the ejection of a control rod from the core, which would cause a rapid increase of reactivity and thermal energy in the fuel [1]. The increase in fuel temperature resulting from an RIA induces a rapid fuel expansion, causing a severe pellet-cladding mechanical interaction (PCMI). This PCMI forces the cladding into multiaxial tension such that the maximum principal strain is in the hoop (i.e., transverse) direction of the cladding tube. The survivability of a cladding irradiated to high fuel burn-up under postulated RIA conditions is thus a response to a combination of the mechanics of loading and the material degradation during a reactor operation.

While such data are available for the axial deformation behavior of cladding tubes, relatively little has been reported in the open literature describing the uniaxial tension behavior in the hoop direction of Zircaloy-4 cladding. Accordingly, it is essential to investigate the uniaxial tension behavior in the hoop direction of high burn-up Zircaloy-4 cladding. In this study, ring tensile tests are applied to obtain the data regarding the uniaxial hoop direction deformation behavior.

2. Experiment

The ring tensile tests were performed in a hot cell. The specimen was the high burn-up Zircaloy-4 cladding from Ulchin Unit 2. The test temperatures were RT(Room Temperature) 135, 200, 400, 600, and 800°C, and the strain rate was set to 0.01/s.

3. Results and Discussion

3.1. Evaluation of the mechanical strength and ductility

The ring tensile tests were performed in a hot cell to evaluate the mechanical strength and ductility of high burn-up Zircaloy-4 cladding whose average burn-up is approximately 57,000 MWd/tU.

To obtain the mechanical strength, 0.2% offset YS(Yield Strength) and UTS(Ultimate Tensile Strength) were evaluated, and UE(Uniform Elongation) and TE(Total Elongation) were also evaluated for the ductility. The hoop stress-strain curves at various temperatures are shown in Figure 1.

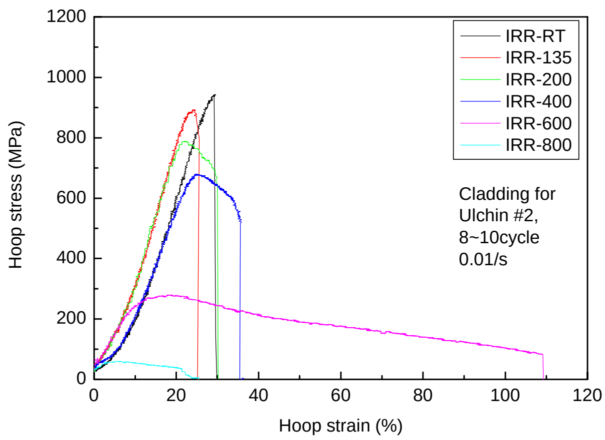


Figure 1. hoop stress-strain curves at various test temperatures

The evaluation results of 0.2% offset YS and UTS were shown in Figure 2.

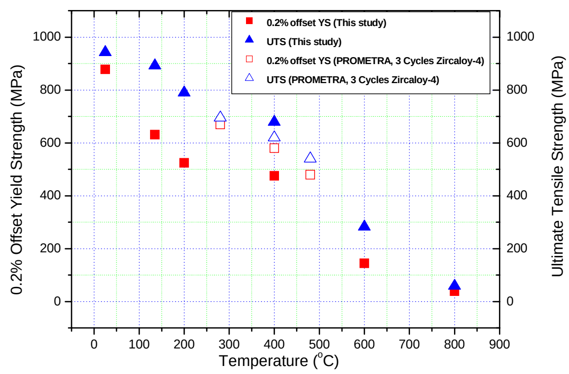


Figure 2. 0.2% offset YS and UTS at various test temperatures

From the figure, it is confirmed that 0.2% offset YS and UTS abruptly decrease with increasing temperature.

The UTS was evaluated to be 942.70 MPa at RT, 678.83 MPa at 400°C, but, it is abruptly diminished to 282.64 MPa at 600°C, achievable in RIA condition. Especially, it decreases to 58.30 MPa at 800°C, extreme condition, which corresponds to 6% of the UTS at RT.

This means that the mechanical strength of the high burn-up Zircaloy-4 cladding sharply decreases in the RIA-relevant temperature ranges.

The evaluation results of UE and TE are shown in Figure 3.

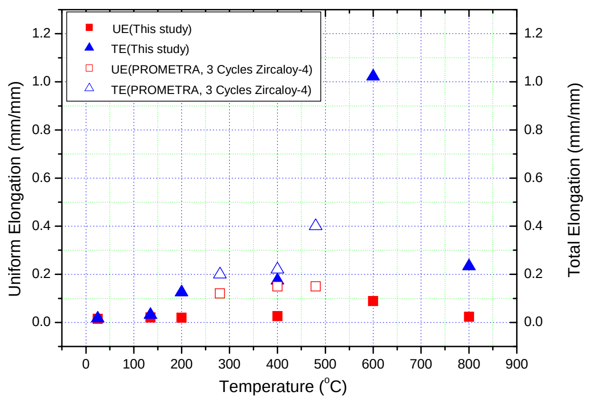


Figure 3. UE and TE at various test temperatures

The result shows that both UE and TE increase with increasing temperature. Especially, they abruptly increase at 600°C, but become lower beyond this temperature. This peculiar behavior was also observed in the PROMETRA program[2] which is a mechanical property relevant test program in conjunction with the CABRI program simulating RIA.

It is believed that this behavior is caused by a phase transformation of the Zircaly-4 cladding material beyond 600°C. Therefore, more experiments are needed to clarify the ductility characteristics over 600°C.

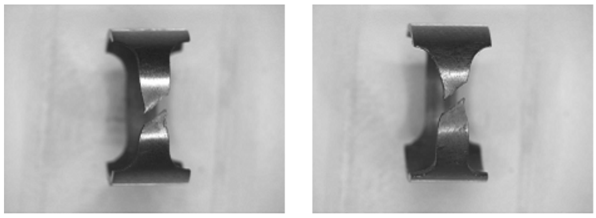
The mechanical properties values evaluated by the ring tensile tests are summarized and tabulated in Table 1.

Table 1. The mechanical properties values at various test temperatures

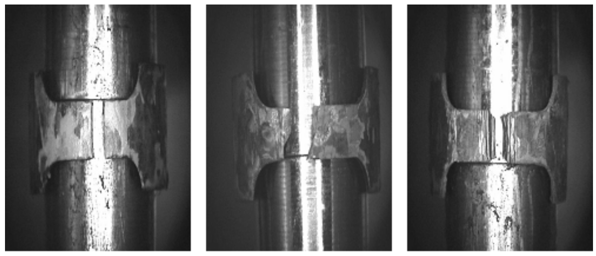
시편 ID	시험온도 (℃)	Strain Rate (/s)	YS (MPa)	UTS (MPa)	UE (mm/mm)	TE (mm/mm)
IRR_RT	RT	0.01	877.91	942.70	0.0148	0.0163
IRR_135	135	0.01	631.49	892.14	0.0207	0.0308
IRR_200	200	0.01	524.77	789.53	0.0197	0.1254
IRR_400	400	0.01	475.51	678.83	0.0264	0.1742
IRR_600	600	0.01	143.86	282.64	0.0887	1.0223
IRR_800	800	0.01	38.87	58.30	0.0237	0.2333

3.2. Fracture characteristics of ring tensile tests

The stereoscope photographs of the specimens after the ring tensile test are shown in Figure 4.



(a) Non-irradiated specimens (RT)



(b) Irradiated specimens (RT, 400°C, 600°C)

Figure 4. Stereoscope photograph of the specimens after ring tensile test

Figure 4 (a) represents the fracture patterns of the non-irradiated specimens at RT, which shows a typical fracture pattern of 45° shear fracture. Therefore it is confirmed that the specimens have very high ductility.

On the contrary, figure 4 (b) represents entirely different fracture patterns from the non-irradiated specimens. The fracture line was revealed to be vertical to the gauge length direction, namely deformation direction even at high temperatures.

This means that even at a high temperature, 600°C, the fracture pattern showed a brittle fracture behavior.

Accordingly, it was revealed that the high burn-up Zircaloy-4 cladding becomes so brittle even at high temperature achievable during the design-basis accident.

4. Conclusions

On the basis of ring tensile tests for high burn-up Zircalay-4 cladding from Ulchin Unit 2, the following conclusions were drawn.

Firstly, mechanical properties abruptly degraded beyond 600°C, which corresponds to design basis accident condition such as RIA.

Secondly, the high burn-up Zircalay-4 cladding showed a brittle fracture behavior even at high temperatures (e.g. over 600°C) to be achievable temperature during RIA.

REFERENCES

[1] Meyer, R. O. et. al., “A Regulatory Assessment of Test Data for Reactivity Initiated Accidents” *Nuclear Safety*, Vol. 37, No. 4, pp. 271-288, 1996.

[2] Averty, X. et. al., “Tensile tests on ring specimens machined in M5 cladding irradiated 6 cycles” *IRSN* 2003/50, 2003.