Behavior of HANA Cladding under a Cyclic Pressurization

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1. Introduction

Fuel cladding, which is one of the most important components in a nuclear fuel system, suffers from a cyclic deformation caused by various kinds of external parameters such as the coolant temperature, the pressure, and the coolant flow rate. Nowadays, the possibility of a low cycle fatigue along the radial direction which is caused by a power oscillation has been proposed in a fuel system [1]. Normally, the power of a reactor is controlled by a control rod by moving it up or down to control the nuclear reaction. When the control rod is driven out, the power of the fuel rod is increased so that the cladding undergoes a radial expansion against the external coolant and vice versa. Such will occur frequently when the vendors adopt a load following operation, which results in cyclic changes of the radial direction to cause a low cycle fatigue. Although no failure regarding a radial fatigue in a fuel cladding has been reported until now, it is essential to accumulate a fatigue life database in terms of a fuel design. The objectives of this study are to construct an internal cyclic pressurization device for a fuel cladding and to produce a stress-life curve of the Zircaloy-4 and the HANA cladding developed by KAERI under a cyclic pressurization.

2. Experimentals

2.1. Test specimen

The claddings used in this study are a commercial grade low tin Zircaloy-4 (Zr-1.3Sn-0.2Fe-0.1Cr) and the HANA-4 (Zr-1.5Nb-0.4Sn-0.2Fe-0.1Cr) cladding developed by KAERI. All the claddings have an outer diameter and thickness of 9.5mm and 0.57mm, respectively. Length of the specimen is 200mm. Final heat treatment was conducted at 470^{o}C to bear a stress-relieved microstructure. Cladding was used in the as as-received condition without any additional surface modification.

2.2. Fatigue test

For the purpose of investigating its fatigue behavior under a cyclic pressurization, an internal pressurization machine for a fatigue testing was devised as shown in Fig. 1. Non-flammable silicone oil was used as a medium to exert an internal pressure on the cladding by virtue of a moving hydraulic cylinder. Diametral changes of the deformed cladding could be measured by using an external LVDT, which was contacted with a cladding surface through a ceramic arm. Low cycle fatigue test, where a constant pressure was applied to the zirconium cladding, was performed in this study. Sawtooth waveform was applied, where the maximum hoop stress was varied from 350 to 500MPa, and where the minimum hoop stress was constant at 78MPa. Test was stopped when the cladding burst. Applied pressure which corresponds to a failure cycle was measured to construct a stress-life diagram (S-N curve) of a zirconium cladding. Test temperature was kept constant at 350^{o}C during the test, which is assumed to be the reactor operation temperature.

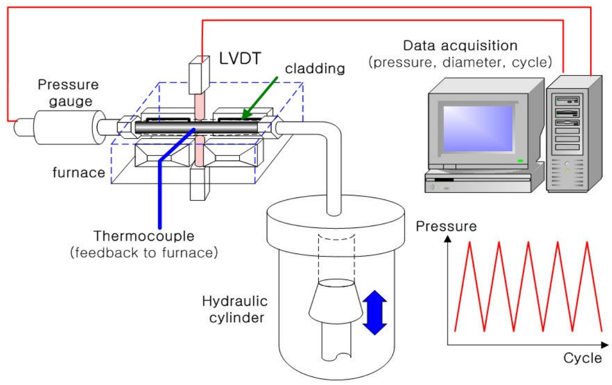

Fig. 1 The cyclic pressurization device designed for the fuel cladding

3. Results and Discussions

Fig. 2 shows the stress-life diagram of the zirconium cladding under a cyclic pressurization. An open symbol denotes that a cladding had ruptured at a given cycle. Closed symbol with an arrow mark represents that a cladding had survived after the given cycles. It was shown that an infinite fatigue life could be expected when the maximum hoop stress was below around 350MPa. From the fatigue behavior of the zirconium material by O'Donnell and Langer [2], the relationship between the applied stress and the failure cycle can be shown as follows.

$$S = \frac{E}{4\sqrt{N}} \ln \frac{100}{100 - RA} + S_e \qquad (1)$$

Where E denotes the elastic modulus, RA means the reduction of an area, S_e is the failure limit. The elastic modulus of zirconium at 350°C can be stated as 74,722MPa [3]. In terms of the reduction of an area, it was measured from the failed tensile specimen after being tested at 350°C, which was 24.8%. Failure limit of the zirconium cladding at 350°C can be proposed as 344.7MPa which is the asymptotic value from Fig. 2. When incorporating the above data, the O'Donnell and Langer relationship for the zirconium cladding tube during a cyclic pressurization can be proposed like the following formula;

$$S = \frac{5288.7}{\sqrt{N}} + 344.7 \qquad (2)$$

When the formula was collated into the data in Fig. 2, the O'Donnell and Langer relationship fitted well into the Zircaloy-4 fatigue data, which revealed that the zirconium cladding satisfies the fatigue relationship proposed by O'Donnell and Langer when it was repeatedly deformed at a frequency of 1Hz. In terms of the alloying element, HANA-4 cladding showed a superior property to the Zircaloy-4 by placing it in the upper part of the stress-life diagram for the Zircaloy-4, which indicates that HANA-4 exhibited a higher fatigue strength than Zircaloy-4 when compared to the same rupture cycle. Alloying element in Nb, which is contained in the HANA-4 cladding to enhance its corrosion property, is known to stabilize the β phase where it reduces the α grain size as well as retards a recrystallization of the α phase [4]. It seems that a finer grain size caused by the addition of Nb will increase a material strength by the Hall-Petch relation to increase its fatigue strength as well as its fatigue life.

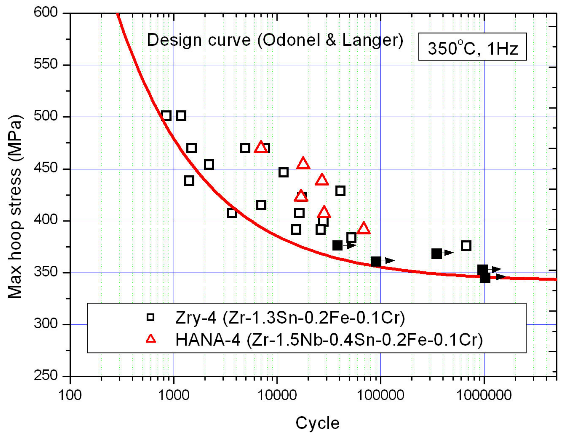

Fig. 2 Stress-life diagram of zirconium cladding with the loading frequency. (Closed symbol with an arrow mark indicates that specimen did not rupture after a given cycle.)

4. Conclusions

1) O'Donnell and Langer relationship can be applied to the fatigue behavior of a zirconium cladding under a cyclic pressurization, where the fatigue limit of the Zircaloy-4 at 350°C is 344.7MPa.
2) HANA-cladding exhibited a superior behavior to the Zircaloy-4 which is attributed the addition of an alloying element such as Nb.

Acknowledgement

This project has been carried out under the Nuclear R&D program by MOST

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