Low Cycle Fatigue Behaviors of the Zircaloy-4 Cladding under the Cyclic Pressurization

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1. Introduction

Zirconium alloys which are used as a cladding materials in PWR, BWR, and CANDU suffer some kinds of degradation caused by the in reactor corrosion. They also suffer the cyclic deformation by the various kinds of external parameters such as coolant temperature, pressure, and other external forces. Among these, two kinds of source in the cyclic load can be found in the fuel cladding. High cycle fatigue which applies in the flexural direction caused by the external flows is found at the fuel cladding. Nowadays, possibilities of high cycle fatigue are greatly diminished by virtue of the spacer grid. Still, low cycle fatigue in the radial direction caused by the power oscillation remains in the fuel cladding [1]. Normally, power of the reactor is controlled by the control rod by moving up or down to control the nuclear reaction. When the control rod is driven out, power of the fuel rod increased so that cladding undergoes radial expansion against the external coolant and vice versa. Such will occur frequently when the vendors adopt load following operation, which results in the cyclic changes of radial direction to cause low cycle fatigue. Although no failure regarding the radial fatigue in the fuel cladding has been reported until now, it is essential to pile up the fatigue life database under in terms of the fuel design. The objectives in this study are to construct the internal, cyclic pressurization facility for the fuel cladding and to produce stress-life curve of the Zircaloy-4 cladding under the cyclic pressurization.

2. Experimentals

2.1. Test specimen

The cladding used in this study is the commercial low tin Zircaloy-4 (Zr-1.3Sn-0.2Fe-0.1Cr) which has the outer diameter and the thickness of 9.5mm and 0.57mm, respectively. Length of the specimen was 200mm. Cladding was used as as-received condition without any additional heat treatment as well as surface modification.

2.2. Fatigue machine

For the purpose of investigating fatigue behavior under the cyclic pressurization, KAERI has devised the internal pressurization machine for the fatigue testing. Fig. 1 shows the schematic illustration of the low cycle fatigue machine for the cladding tube. Pressure of the cladding can be controlled to the value between 0 to 80Mpa, which equivalent hoop stress is ranged up to 630MPa. Non-flammable silicone oil was used as a medium to exert internal pressure on the cladding. Diametral changes of the deformed cladding can be measured by the external LVDT connected to cladding surface inside of furnace through the ceramic arm. Two kinds of testing mode can be performed. The one is applying constant pressure during fatigue test (ΔP =constant), the other is applying constant hoop stress by compensating diametral changes ($\Delta\sigma$ =constant) during fatigue test. Furthermore, it can control its loading frequency to test the various kinds of waveform, such as sawtooth waveform whose frequency ranges can be changed below 1Hz, trapezoidal waveform where ramping rate as well as holding time can be controlled.

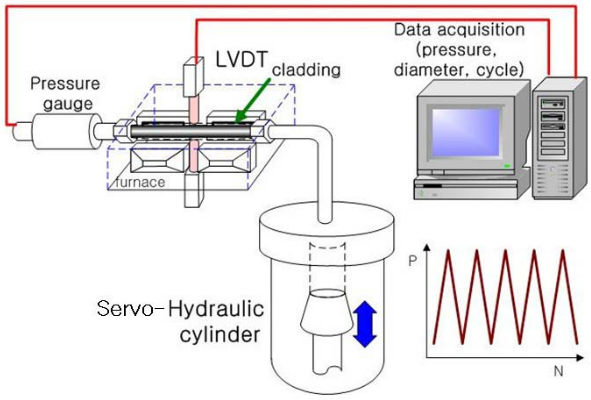

Figure 1. Schematic illustration of internal pressurization machine for fatigue testing

2.3. Fatigue test

It was performed that stress controlled, low cycle fatigue test where constant pressure was applied at the Zircaloy-4 cladding in this study. Maximum pressure was varied from 40MPa to 60MPa, where minimum pressure was set 10MPa. Sawtooth waveform was applied which frequency was 1Hz. Test stopped when the cladding burst. Applied pressure which corresponds to failure cycle was measured to construct stress-life diagram (S-N curve) of the Zircaloy-4 cladding. Test temperature maintained constant at 350℃ during the test.

3. Results and Discussions

3.1. Stress- life diagram of Zircaloy-4 cladding

Fig. 2 shows the stress-life diagram of Zircaloy-4 cladding under the cyclic pressurization. It was shown that inverse relationships between the applied stress and the failure cycle. An arrow mark represents the cladding survived after the given cycles. Maximum hoop stress, where infinite fatigue life exhibits below the stress, was shown around 350MPa. From the fatigue relationship of Zircaloy component by O'Donnell and Langer [2], stress and failure cycle can be shown as follows.

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

Where E denotes the elastic modulus (=95,550MPa in Zirconium), RA means the reduction of area where it can be indirectly calculated by the failure strain of Zircaloy-4 after tensile specimen, S_e is the failure limit which is the value of 341.6MPa, provided that circumferential failure limit can be calculated by multiplying 2 on the axial fatigue limit of 170.8MPa [2]. Collating the data into one figure, O'Donnell and Langer relationship fitted into the Zircaloy-4 fatigue data, which revealed that Zircaloy cladding under cyclic internal pressurization follows fatigue behavior by O'Donnell and Langer relationships.

3.2. Failure process of Zircaloy-4 cladding under the cyclic pressurization

Visual appearance of the failed specimen showed similar to that of biaxial burst specimen, that is, specimen severely ballooned at region near the rupture site. Ballooned diameter corresponds to the applied pressure, whereas uniform diameter below 20mm of failed region decreased when the applied pressure increased. Such a trend may have a relation with the creep of the Zircaloy-4. Fractographic observation on the Zircaloy-4 surface also showed ductile rupture around the crack mouth, without finding any of the signs regarding fatigue striation. This implies that failure process of Zircaloy-4 cladding under the cyclic pressurization somewhat differs from that of typical fatigue process. Proposed failure models can be described as follows; Cladding continuously balloons and thins by the creep process as cyclic pressure is applied. When the thinned cladding cannot maintain the applied pressure, cladding loses its stability and ruptures at the certain cycles.

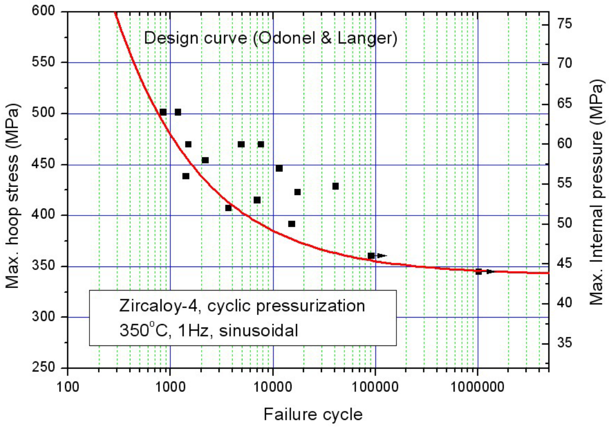

Figure 2. Stress-life diagram (S-N curve) of the unirradiated, as received Zircaloy-4. Arrow mark represents the specimen survived after the given cycle.

4. Conclusions

Low cycle fatigue behavior of Zircaloy-4 cladding under the cyclic pressurization was investigated in this study. Cyclic pressurization machine for cladding tube was devised and the followings can be summarized;

1) Fatigue behavior of the Zircaloy-4 cladding under the cyclic pressurization can be applied to O'Donnell and Langer relationship.
2) Creep-fatigue interaction rather than fatigue only had an influence on the failure of Zircaloy-4 cladding under the cyclic pressurization.

Acknowledgement

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REFERENCES

[1] A. Soniak, S. Lansiart, J. Royer, J-P. Mardon and N. Waeckel, Irradiation Effect on Fatigue Behavior of Zircaloy-4 Cladding Tubes, Zirconium in the Nuclear Industry, 10th Int. Symp., ASTM STP 1245, pp. 549-558, 1994.

[2] W. J. O'Donnell and B. F. Langer, Fatigue Design Basis for Zircaloy Components, Nucl. Sci. and Eng., 20, pp. 1-12, 1964.