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Low Cycle Fatigue Property of Zirconium Cladding

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1. Introduction

Fuel cladding, which protects uranium fuel from a flowing coolant in a light water reactor (LWR), suffer from a cyclic deformation due to the various kinds of external parameters such as the coolant temperature, the pressure, and the coolant flow rate. Above all, there remains the possibility of a low cycle fatigue in the fuel cladding along the radial direction which is caused by a power oscillation [1,2]. 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 the fuel cladding has been reported until now, it is essential to accumulate a fatigue life database in terms of a fuel design. From the standpoint of a radial fatigue of the fuel cladding, Soniak [3] proposed a stress-life diagram of unirradiated and irradiated Zircaloy-4 tubes under a cyclic pressurization. However, lots of fatigue data regarding fuel cladding under a cyclic pressurization is needed at present.

The objectives of this study are to produce a stress-life curve of zirconium cladding under a cyclic pressurization, as well as to propose the relevant fatigue process of a fuel cladding during a cyclic pressurization.

2. Experimentals

2.1. Test specimen

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

2.2. Fatigue test

Fig. 1 shows the low cycle fatigue machine for a cladding tube. Hydraulic cylinder moves up and down to apply a cyclic pressure to the cladding specimen so that the pressure of the cladding can be controlled to a value between 0 to 80Mpa, which equivalent hoop stress ranges up to 630MPa. Non-flammable silicone oil was used as a medium to exert an internal pressure on the cladding. Constant pressure difference (Δ P=constant) during a fatigue test was applied in this study.

Low cycle fatigue test, where a constant pressure difference was applied to the Zircaloy-4 cladding, was performed in this study. Sawtooth waveform was applied, where the maximum hoop stress was varied from 310MPa to 470MPa, whereas the minimum hoop stress was constant as 10MPa. Test was stopped when the cladding burst or the cycle elapsed over 1,000,000 times or the oil leaked too much through the mechanical seal to progress additional test. Maximum hoop stress which corresponds to the failure cycle was measured to construct a stress-life diagram (S-N curve) of the Zircaloy-4 cladding. Test temperature was kept constant at 350^{o}C during the test, where the thermocouple was located at the midpoint of the specimen to measure the test temperature in 350^{o}C. Temperature at the side of each chamber was 15~20^{o}C lower than at the midpoint.

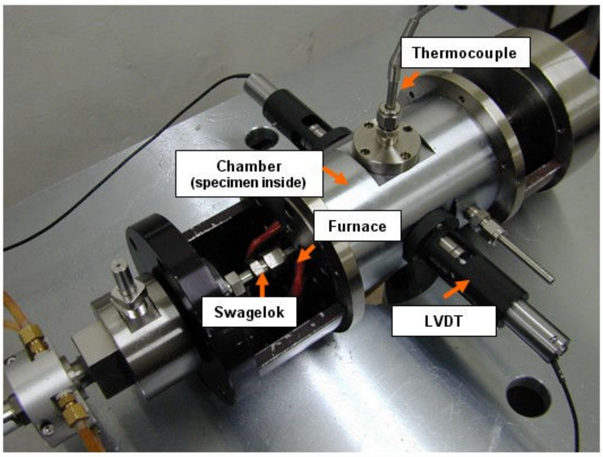

Fig. 1 The cyclic pressurization device for testing low cycle fatigue

3. Results and Discussions

Fig. 2 shows the stress-life diagram of the Zircaloy-4 cladding under the cyclic pressurization. Inverse relationships between the applied stress and the failure cycle were observed. An open symbol denotes that a cladding had ruptured at the given cycle. Closed symbol with an arrow mark represents that a cladding had survived after the given cycles. It was shown that infinite fatigue life could be expected when the maximum hoop stress was below around 350MPa, followed after O'Donnell and Langer relationship. When the formula was collated into the data in Fig. 3, the O'Donnell and Langer relationship fitted into the Zircaloy-4 fatigue data well, which revealed that Zircaloy-4 cladding when repeatedly pressurized at 1Hz satisfies the fatigue relationship proposed by O'Donnell and Langer.

Loading frequency is one of the important factors which affect a cladding behavior under a cyclic deformation. Cladding shows a fatigue relationship which correlates with the O'Donnell and Langer equation when the loading frequency is 1Hz. On the other hand, the fatigue property of the cladding soon deviates from the O'Donell and Langer relationship as the loading frequency becomes lower. When the loading frequency is 0.5Hz, the maximum hoop stress to cause a rupture became lower when compared to the 1Hz condition. Finally, the behavior at the 0.1Hz condition is such that it cannot discriminate between the 0.1Hz fatigue curve and the pure diametral creep. When the loading frequency is low below 1Hz, it is shown that creep governs the whole process in the Zircaloy-4 cladding.

Fracture appearance of the failed claddings also supports the above postulation that a diametral creep rather than a pure fatigue constitutes the main deformation process during a cyclic pressurization test. Fractographic observation of the surface after a cyclic pressurization also showed a ductile rupture around the crack mouth, without any signs of a fatigue striation. The main reasons why the fatigue striation did not show are due to the thin cladding thickness. Normally, the fatigue process of the metal can be divided into two processes. One is the initiation of the fatigue crack which is originated from either the localized slip band or the defect (stage I). The other is the propagation of the initiated fatigue crack where it leads to the metal failure (stage II). At the stage II, crack continuously opens and closes at each maximum and minimum stress to complete single fatigue cycle, leaving a typical fatigue striation. Fatigue process of the zirconium cladding, however, differs from that of the typical metal because of its thin thickness. Creep caused by the positive mean hoop stress continuously thins the cladding thickness to reduce the load bearing capability. When the thickness of cladding is too small to maintain the cyclic stress, the cladding will burst all at once, without leaving any signs of typical fatigue process, such as striation.

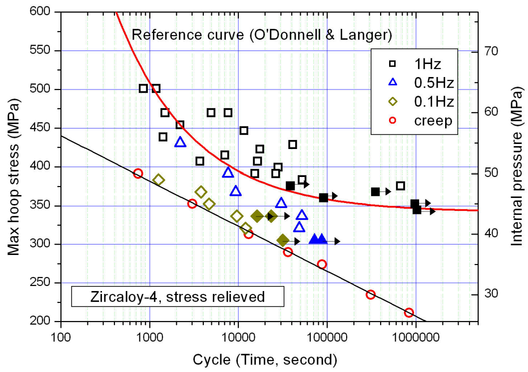

Fig. 2 Stress-life diagram of zirconium cladding with the loading frequency.

4. Conclusions

Deformation behavior of Zircaloy-4 cladding under the cyclic pressurization was investigated in this study. O'Donnell and Langer relationship can be applied to the fatigue behavior of Zircaloy-4 cladding under the cyclic pressurization at 1Hz. When the applied frequency decreased down to 0.1Hz, the stress-life diagram converged into a pure diametral creep diagram. It seemed that a combined creep-fatigue interaction rather than a pure fatigue had an influence on a failure of the Zircaloy-4 cladding under a cyclic pressurization at 350°C.

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