A Study on hoop directional creep characteristics of Zr-based nuclear fuel cladding

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1. Introduction

An understanding of high temperature deformation behavior of the nuclear fuel cladding in a wide range of stresses is essential to warrant the mechanical integrity of the discharged cladding under the interim dry storage condition. In the dry storage, the cladding temperature may be higher than that in the wet storage and can reach up to 400℃. The cladding under the interim dry storage condition may degrades or end to fail some possible mechanisms.

Among the failure mechanisms causing the degradation of mechanical properties or failure of the fuel cladding under the dry storage condition, the creep mechanism is believed to be most dominant. Especially, the hoop-directional creep property is concern due to the difference of pressure between fuel-cladding gap and storage environment. Creep behaviors of Zr and its alloys has been studied over several decades[1, 2, 3]

In case of discharged spent fuel rods, the rod pressure is somewhat different from rod to rod. Accordingly, the applied stress for the discharged fuel rod have an effect on creep life time under the dry storage condition.

Accordingly, it is worthwhile to evaluate creep life time of fuel rod with increasing hoop stress. In this study, experimental results concerning the hoop-directional creep properties of as-received Zr alloy cladding tube and pre-hydrided Zr alloy cladding tube are introduced.

2. Creep Behavior

In the dry storage environment, the spent fuel cladding is placed in high temperature and hoop stress conditions. Creep rate can be expressed as the following equation.

$$\varepsilon = K\sigma^{n}\exp(-Q/RT) \qquad (1)$$

ε : creep rate
σ : hoop stress of the spent fuel cladding
Q : activation energy
R : gas constant
T : absolute temperature of the cladding
K : proportional constant
n : stress exponent

The above equation suggests that the temperature and hoop stress of the spent fuel cladding are the main driving forces for the creep deformation. Accordingly, it is crucial to limit the maximum temperature of the stored fuel cladding and the maximum hoop stress and fuel rod internal pressure in order to maintain the mechanical integrity of the fuel cladding tube.

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3. Experimental Methods and Results

3.1 Experimental conditions

The hoop directional creep test specimens used in this study are pre-hydrided Nb-containing Zr alloy cladding tube (alloy A).

The dimensions and shape of the hoop-directional creep specimen were designed in order to ensure that any deformation is limited to the gage section of the specimen, so that the uniform uniaxial hoop strain in the gage section could be at its maximal[2]. The gage sections of the specimens were oriented at the top and bottom of the half cylinder of the grip, such that a constant curvature of the specimen can be maintained during a creep deformation. The interface was lubricated with a graphite-containing vacuum grease lubricant at the beginning of each test to minimize a loss of the applied load. The hoop directional creep tests were performed with the Instron Servohydraulic System, Model 8562 at 500°C and 550 °C.

The applied hoop stress are 141, 145, 163, 169, 193, 241 MPa in 500°C creep tests, and 105, 115, 122, 127, 129, 158 MPa in 550°C creep tests.

3.2. Experimental Results

Hoop directional creep tests of Nb-containing Zr alloy tube (Alloy A) with hydrogen content of ~130 ppm were performed at 500°C and 550°C. Fig. 1 shows creep life time of Alloy A with increasing hoop stress at 500°C. When the applied hoop stress is 141 MPa, the creep life time was 65.1 hr, and then the creep life time was decreased with increasing hoop stress of the cladding material. The decrease rate of creep life time with increasing hoop stress was diminished with increasing hoop stress, and the creep life time was saturated over the hoop stress of ~200MPa. The hoop stress of 200MPa corresponds to the hoop stress ratio to yield stress of 0.5 at 500°C.

Fig. 2 also shows the behavior at 550°C. The behavior of the creep life time with increasing hoop stress was similar to that at 500°C. When the applied hoop stress is 105 MPa, the creep life time was 200 hr, and then the creep life time was decreased with increasing hoop stress of the cladding material. The decrease rate of creep life time with increasing hoop stress was diminished with increasing hoop stress, and the creep life time was saturated over the hoop stress of ~130MPa. The hoop stress of 130MPa corresponds to the hoop stress ratio to yield stress of 0.45 at 550°C.

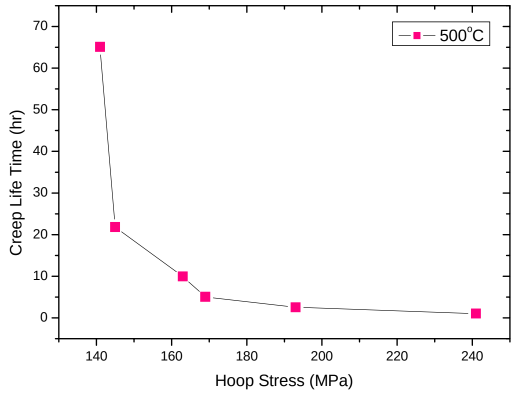

Fig. 1. Creep life time of Zr alloy (Alloy A) with increasing hoop stress at 500°C

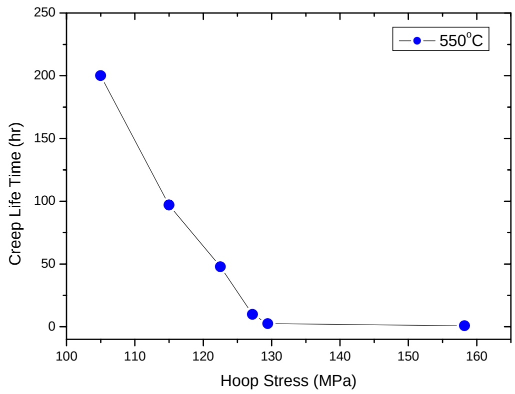

Fig. 2. Creep life time of Zr alloy (Alloy A) with increasing hoop stress at 550°C

5. Summary

The hoop directional creep tests for Nb-containing Zr alloy cladding tube (Alloy A) with hydrogen content of ~130 ppm were performed in the temperature range from 500°C to 550°C. The creep life time was decreased sharply time with increasing hoop stress and saturated over the hoop stress ratio to yield stress of 0.5 and 0.45 at 500°C and 550°C, respectively.

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