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Estimation of Creep Deformation for the Dual-Cooled Cladding Tubes

Yang-Il Jung [a,*], Byoung-Kwon Choi [a], Jeong-Yong Park [a]
[a]LWR Fuel Technology Division, Korea Atomic Energy Research Institute,
989-111 Daedeok-deaero, Yuseong, Daejeon, 305-353, Republic of Korea
[*]Corresponding author: yijung@kaeri.re.kr

1. Introduction

The concept of a dual-cooled fuel was developed to achieve low temperature operation along with high power density [1-3]. Dual-cooled fuel consists of two claddings and annular pellets, and is designed to provide double coolant channels. Korea Atomic Energy Research Institute (KAERI) is doing the R&D project for the development of dual-cooled fuel technology [3].

There are two kinds of tubes, i.e. an inner and outer cladding tube, which would deform in reverse directions by the creep process. The creep rates are far different between the opposed creep modes [4]. Also, differences in gap closure for the two claddings can be expected, which affect the heat split performance directly. Therefore, the creep should be analyzed for the safe design of dual-cooled fuel. In this paper, creep deformations were estimated based on the experimental and analytical methods for the dual-cooled cladding tubes.

2. Methods and Results

2.1 Experimental Procedures

In our previous report [4], the creep specimens simulating the dual-cooled tubes were fabricated and tested under both high-pressure and high-temperature conditions. A detailed sample preparation was described in the report [4]. The dimension of the inner cladding tube was 9.5 mm in outer-diameter and 0.57 mm in thickness. The outer cladding tube was 15.9 mm in outer-diameter and 0.89 mm in thickness, which was 0.02 mm thicker than the designed outer cladding tube. Creep was tested under an external pressure of 9.5 MPa and 11.5 MPa at 380℃. The test was performed in a pressurized steam atmosphere in an autoclave, and the pressure was controlled by changing the amount of water. The test pressure is identical to the pressure difference between pressurized coolant and the inside of the claddings in a real operational condition. Table 1 summarizes the test conditions along with the three types of microstructures, i.e. stress-relieved (SR), partial recrystallized (PRX), and full recrystallized (RX).

2.2 Creep Behavior

Fig. 1 shows the radial creep strains for the dual-cooled cladding tubes. Inner cladding tubes under the tensile stress were crept out, and outer ones under the compressive stress were crept down. Several samples that deformed too much were collapsed before the end of the test. The creep rates for the tensile creep-out were about two times faster than that of the compressive creep-down. The secondary creep rate for the SR tube was the highest, and that for the RX one was the lowest. The rates were 10 to 5 times larger in SR and PRX than in RX microstructures. It was also observed that the creep behavior of each cladding was independent of the facing cladding tubes.

Table 1. Experimental conditions for the simulated creep test

No.	Pressure difference	Hoop stress		Materials	
		Inner	Outer	Inner	Outer
1	9.5 MPa	+74	–80	SR	SR
2	9.5 MPa	+74	–80	RX	RX
3	9.5 MPa	+74	–80	SR	RX
4	9.5 MPa	+74	–80	RX	SR
5	9.5 MPa	+74	–80	PRX	PRX
6	11.5 MPa	+90	–97	SR	SR
7	11.5 MPa	+90	–97	RX	RX
8	11.5 MPa	+90	–97	PRX	PRX

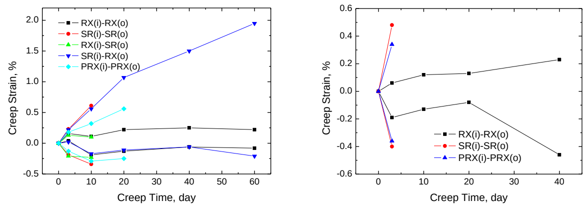

Fig. 1. Creep strains for the simulated dual-cooled cladding tubes under a 9.5 MPa (left) and 11.5 MPa (right) external pressure at 380℃.

Creep strain and deformation of the simulated dual-cooled cladding tubes are demonstrated in Fig. 2. The inner cladding deforms much faster than the outer cladding; however, the different diameters between the two claddings induced similar creep deformations. In the SR microstructure, the radial deformation was +19 mm in the inner cladding, and –0.14 mm in the outer cladding after 60 days of creep test. It is concluded that the relative deformation was 34% larger in the inner cladding tubes.

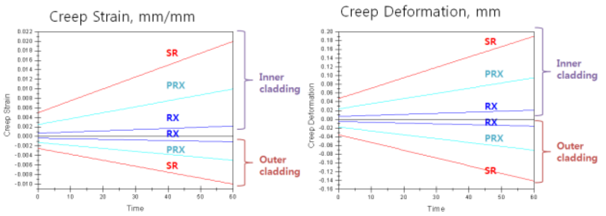

Fig. 2. Estimated creep strain (left) and deformation (right) for the simulated dual-cooled cladding tubes.

2.3 Model Estimation

Three different models for the irradiation creep were utilized to estimate the radial creep deformation for the dual-cooled cladding tubes. Creep strain by Franklin's model is described as [5]

$$\epsilon = At^m\Phi^p\sigma^n \exp\big(-\frac{Q}{T}\big)$$

where A is a material constant (1.11E-13 for Zircaloy-4), t the time (hours), Φ the neutron flux (n/cm^2.s, E>1 MeV), σ the hoop stress (MPa), T the temperature (K), and Q the activation energy (1173), and the powers were m=0.682, p=0.550, and n=0.579, respectively. The model was directly applied for the outer cladding's creep-down, and doubled the strains for the inner cladding's creep-out. Another model was an old version of MATPRO. The creep rate based on Zircaloy-2 is explained as [5]

$$\dot{\epsilon} = K\Phi\big(\sigma + B\exp(C\sigma)\big)\exp\big(-\frac{10000}{RT}\big)t^{-0.5}$$

where the constants were K=5.129E-29, B=7.252E2, C=4.967E-8, and R=1.987 (cal/mol.K), and T is the cladding average temperature (K), t the time (sec), Φ the fast neutron flux (n/m^2.sec), and σ the circumferential stress (N/m^2). Since this model was deduced from the internal pressurized samples, the creep rates were halfed for the outer cladding tube. The other model was the recent version of MATPRO as in the following equation [6]

$$\dot{\epsilon} = AB - \int_0^t B\exp\big[-(t-t')(\frac{\Phi}{\xi} + \frac{1}{\gamma})\big]\dot{\epsilon}(t')dt'$$

where A, B, ξ, γ are functions depending on the temperature and circumferential stress, T the temperature (K), t the time (sec), and Φ the fast neutron flux (n/m^2.sec). Since MATPRO simulates the irradiation creep under compressive stress, the creep-out of the inner cladding was calculated by two-fold. With conditions of the neutron flux of 5.4E17 n/m^2.s, and the temperature and pressure difference of 350℃ and 10 MPa, the creep deformations for each model were calculated as shown in Fig. 3. All models estimated 23–28% larger creep deformation for the inner cladding tube. Both Franklin's model and old MATPRO predicted the continual increase in the creep deformation. In contrast, the recent MATPRO even simulated the saturation of the deformation due to the pellet-to-cladding contact. In the dual-cooled cladding tubes, the former two models are desirable to adopt because of the structural difference between the solid fuel and dual-cooled annular fuel.

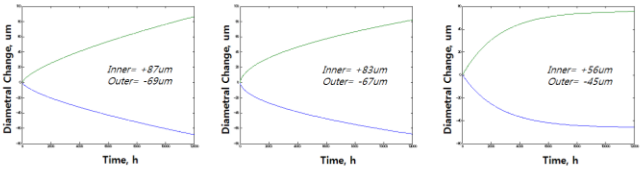

Fig. 3. Calculated creep deformation in 12000 h for the simulated dual-cooled cladding tube according to the Franklin's model (left), old MATPRO code (middle), and recent MATPRO (right).

3. Conclusions

The relative creep deformation was about 34% larger in the inner cladding tubes according to the experimental results. The difference was 23–28% based on the model estimation. It is desirable for the heat-split performance that the inner cladding tube deforms faster than the outer one. If one considers the swelling of annular fuels – increase in both inner and outer diameters – the inner cladding tube should have much higher deformation rates. The cladding types shall be determined after considering the swelling, irradiation growth, and axial creep, synthetically.

Acknowledgement

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