Thermal Creep Modeling of Zircaloy-4 Fuel Cladding

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1. Introduction

The cladding creep behavior that is one of the most important factors in fuel rod design is occurred by the difference between coolant and rod internal pressures. The out-of-reactor thermal creep behavior is analyzed by the tube diameter increase after the isothermal and internal pressurization test method.

The creep deformation of the cladding is affected by not only alloying element but the amount of cold reduction during the final pilgering. As the Zr alloy has the different creep mechanism dependent upon the temperature and applied stress level, the mechanism controlling the creep behavior can be estimated by the activation energy and stress exponent[1].

The objective of this study is to find the creep mechanism and thermal creep model equation for stress relief annealed Zircaloy-4 cladding manufactured by the different final pilgering processes.

2. Experimental Method

The as-received Zircaloy-4 claddings were manufactured in different sizes with the final thermo-mechanical parameters given in Table 1. The as-received conditions of the tubes were cold-worked and stress-relieved state on various annealing conditions.

Table 1. Final Thermo-mechanical Parameters of Fuel Cladding Tubes for Creep Test

	OD×ID (mm)	Q	RA (%)	Anneal (°C/hr)
A	9.50×8.357	3.5	78.5	480/5
B	10.16×8.926	3.4	80.4	480/5
C	9.144×7.874	6.1	82.0	490/5
D	9.50×8.357	2.0	82.5	460/7

Nominal 15 cm long specimens were welded with a special end cap for preventing leakage of internal pressure gas. Theses samples were assembled with a tube creep testing apparatus using Swagelok-type fitting. After attaining a specified test temperature in 3–zone furnace, the specimens were internally pressurized by argon gas. During the test, the specimen temperature was maintained within ±3 K and the internal pressure was controlled in a negligible variation. The diametral change of the specimen was periodically measured with a digital micrometer at three different axial locations of the specimen. Most of the tests were duplicated to reduce uncertainty. The hoop stress of a specimen w, σ_θ, was predicted in accordance with the formula, $\sigma_\theta=0.5P_iD_m/w$, where P_i is the internal pressure , D_m is the mid-wall diameter, and w is the thickness of the tube.

3. Results and Discussion

As shown in Fig. 1, the diametral creep strain of stress relief annealed Zircaloy-4 cladding was proportional to the amount of area reduction at the final pilgering process.

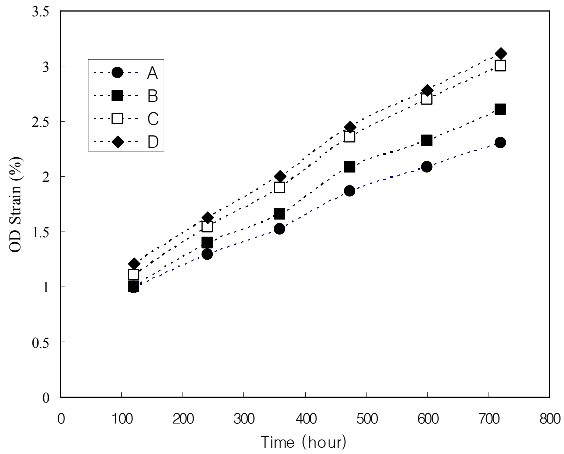

Figure 1. Creep strain of each cladding tubes tested at 400°C and 120 MPa

Therefore, the creep strain could be estimated as a function of area reduction at the final pilgering process. From the results of creep strain for several temperature in the range of 350 ~ 400°C and stress level in the range of 80 ~ 150 MPa, the creep rate equation was developed as a function of mid-wall creep strain and effective stress. The experimental stress level is so high that the relationship proposed by Ardell and Ashby was used as a basic equation. The temperature dependence of creep in Zr alloy could be expressed as the Arrehenius equation based on the dislocation climb-glide motion.

On the basis of the following basic equation,

$$\varepsilon = \varepsilon_o[1-\exp(-k\sqrt{\dot{\varepsilon}\, t})] + \dot{\varepsilon}\, t$$

$$\dot{\varepsilon} = A\exp(\frac{C\sigma}{E})\exp(-\frac{Q}{RT})$$

ε : total mid-wall creep strain (%)

$\dot{\varepsilon}$: steady state thermal creep rate at mid-wall (%/day)

ε_o : saturated primary creep strain = B $\dot{\varepsilon}^b$

σ : effective stress (MPa)
Q : activation energy, J/mol
A, B, C, b, k : constant
E : elastic modulus, MPa

the activation energy obtained from the results is 225~250kJ/mol. This value is similar to Holmes'[2] result(245kJ/mol) obtained from the annealed - 20% cold rolled Zircaloy-2 and Ardell's[3](210~327 kJ/mol) obtained from the pure Zr.

The thermal creep model equation established for the Zircaloy-4 claddings taking into consideration of area reduction at final pilgering process could be expressed as

$$\dot{\varepsilon} = 6.78 \times 10^{15} \left(\frac{RA^2}{1 - RA^2}\right) \exp\left(3471.8 \frac{\sigma}{E}\right) \exp\left(-\frac{30016}{T}\right)$$

E : elastic modulus, ksi (=14650 –5.58T (°F))

$$\varepsilon = 1.6 \times 10^{-4} RA^2 \dot{\varepsilon}^{0.082} [1 - \exp(-3.5\sqrt{\dot{\varepsilon}\, t})] + \dot{\varepsilon}\, t$$

The good correlation between the measured creep rate and the predicted rate by using above equation is shown in Fig. 2.

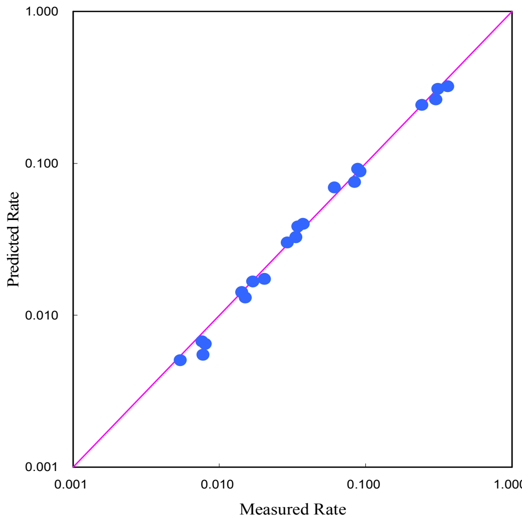

Figure 2. Comparison of measured and predicted creep rates

4. Conclusion

The creep rate of stress relief annealed Zircaloy-4 cladding was proportional to the amount of area reduction at the final pilgering. The thermal creep model equation taking into consideration of area reduction at final pilgering step was developed and has shown a good correlation with the measured creep rate.

REFERENCES

[1] Franklin, D.G., Creep of Zirconium Alloys in Nuclear Reactors, 1993.
[2] Holmes, J.J., Journal of Nuclear Materials, Vol. 13 (1964), P. 137.
[3] Ardell, A.J., Transactions of the AIME, Vol. 239 (1967), PP. 1547-1556.