The Prediction of Creep behaviors of Zircaloy-4 Using Uniaxial Stress Relaxation

Tae-hoon Kim [a], Ju-seong Kim [b], Ho-a Kim [a], Yong-soo Kim [a*]
[a]*Department of Nuclear Engineering, Hanyang University, Seoul, 133-791, Korea*
[b]*Korea Atomic Energy Institute, 150 Deokjin-dong, Yuseong-gu Daejeon, 305-353, South Korea*
[*]*Corresponding author: yongskim@hanyang.ac.kr*

1. Introduction

Zirconium alloys have been used as a reactor component material because of their favorable neutronic properties, good mechanical behavior at elevated temperature and high corrosion resistance. In reactor operation condition, creep is one of the significant degradation mechanisms in zirconium alloys **[1]**. Recently, creep is known as a critical factor which threatens the integrity of cladding with hydride re-orientation in dry storage condition **[2]**. However, the evaluation of creep is not easy, because creep test requires a considerable time. It is known that stress relaxation and creep are correlated analytically. Creep behavior can be derived from stress relaxation test with a relatively short time **[3]**. In this paper, creep behavior of Zircaloy-4 is predicted using uniaxial stress relaxation.

2. Experimental

2.1 Material

The material used in this work is a recrystallized Zircaloy-4 plate which was cold-rolled in the longitudinal direction. The sheet-type specimens with having gauge section of 25.4×3.7 mm and thickness of 0.5 mm were cut from the plate as shown in Fig. 1. The sheet-type specimens which is smaller size than ASTM E8 **[6]** were manufactured in transverse direction.

2.2 Uniaxial stress relaxation test

The Stress relaxation test was performed along the transverse direction using an universal testing machine (Instron 5582) at 400 °C. The specimens were heated up to 400 °C at heating rate of 10 °C/min and then maintained at 400 °C for 10 hours to stabilize temperature prior to the tensile displacement. The tensile strain rate of 1×10^{-3}/s was used in reference to ASTM E8 **[6]**. The tensile stress was applied until displacement is 0.337-2.521 mm. When these displacements were reached, the tensile strain was held and stress relaxation was measured for about 8 hours.

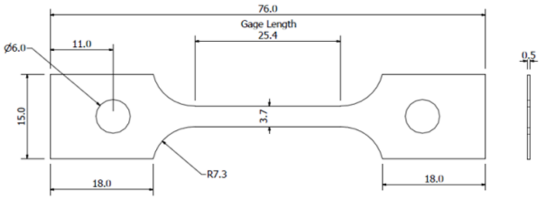

Fig. 1. Tensile specimen geometry

3. Results and discussions

3.1 Stress relaxation

Tensile stresses of 65 MPa, 127 MPa, 164 MPa and 187 MPa were derived from tensile strains of 0.337 mm, 0.489 mm, 0.997 mm and 2.521 mm respectively. Generally, stress relaxation curve can be represented by exponential equation **[3]**. In this study, applied this equation form, curve-fit of the relaxation test data was performed to minimize the fluctuations of data. Fig. 2 shows fitted relaxation results.

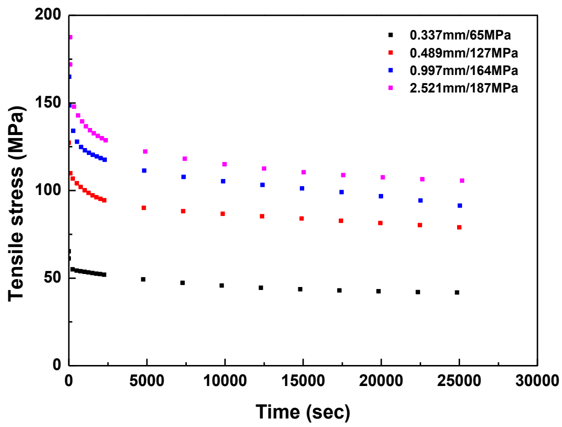

Fig. 2. Fitted relaxation curves

3.2 The prediction of creep behaviors

Assuming that the total strain (ε_T) consists of elastic (ε_E) and inelastic (ε_I) strain, stress relaxation can be mathematically expressed by following equations **[3, 4]**.

$$\varepsilon_T = \varepsilon_E + \varepsilon_I \tag{1}$$

$$\frac{d\varepsilon_T}{dt} = \frac{d\varepsilon_E}{dt} + \frac{d\varepsilon_I}{dt} = 0 \tag{2}$$

$$\frac{d\varepsilon_I}{dt} = -\frac{d\varepsilon_E}{dt} \tag{3}$$

$$\frac{d\varepsilon_I}{dt} = -\frac{1}{E}\frac{d\sigma}{dt} \tag{4}$$

where σ is stress, t is time and E is elastic modulus.

Fig. 3 shows strain rate-stress curves obtained through these equations. Pseudo strain-stress curves (Fig. 4) can be derived from vertical cut taken at 10 strain rates point and then estimated creep curves (Fig. 5) from horizontal cut taken at corresponding stress points in pseudo strain-stress curves. The saturated primary creep strain (ε_{sat}) were derived in estimated creep curves which were calibrated. The saturated primary creep strains were 0.029 mm/mm at 100 MPa and 0.033 mm/mm at 120 MPa. Since the steady state creep rates ($\dot{\varepsilon}_{ss}$) are too low in this stage, it is considered that they are unreliable. Thus, the steady state creep rates were obtained by an analytic method.

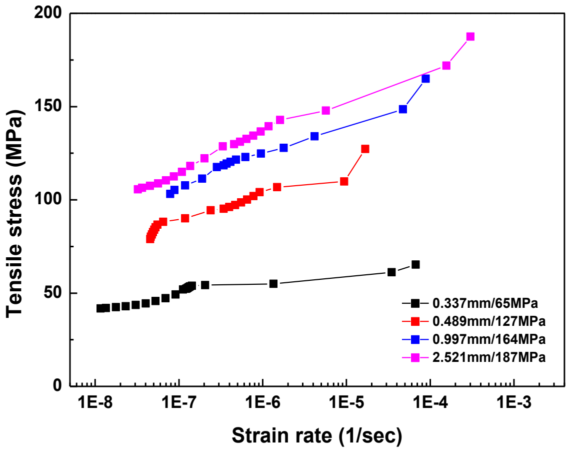

Fig. 3. Strain rate-stress curves

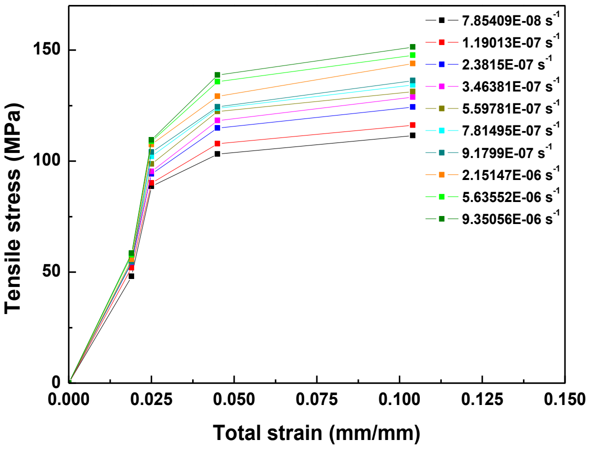

Fig. 4. Pseudo strain-stress curves

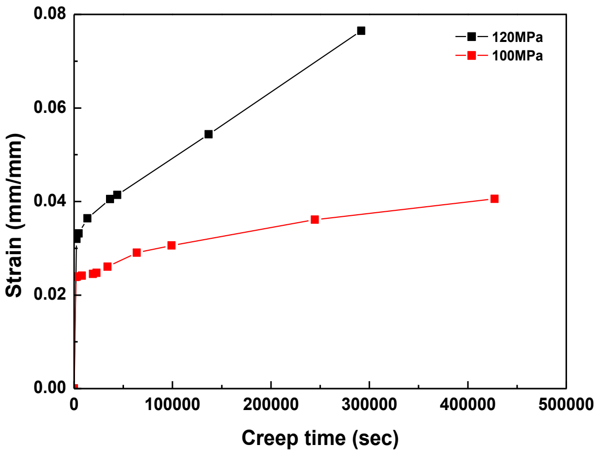

Fig. 5. Estimated creep curves

As Stress relaxation and creep are related analytically by following equations **[3, 5]**.

Stress relaxation: $\sigma = \sigma_0 \exp(-k^p t^p)$ (5)

Creep: $\varepsilon = \frac{k^p}{E} t^p \sigma_c$ (6)

where σ_0 is maximum tensile stress and σ_c is the loading stress in creep. The experimental constants of p and k can be derived by these equations. In this study, p and k were 0.235 and 3.36×10^{-6} respectively. The steady state creep rates ($\dot{\varepsilon}_{ss}$) can be generated in curves which reflect the curvature of stress relaxation curves. The steady state creep rates ($\dot{\varepsilon}_{ss}$) were $2.48 \times 10^{-8} s^{-1}$ at 100 MPa and $2.22 \times 10^{-7} s^{-1}$at 120 MPa. Using the present ε_{sat} and $\dot{\varepsilon}_{ss}$, the final creep curves were predicted in Fig. 6. The predicted creep behavior for 100 MPa was consistent with the experimental data but that for 120MPa was not (Table 1).

Table 1. Experimental and predicted creep results

	Experiment		Predicted	
	100MPa	120MPa	100MPa	120MPa
$\dot{\varepsilon}_{ss}$ (s^{-1})	2.5×10^{-8}	3.04×10^{-7}	2.48×10^{-8}	2.22×10^{-7}
ε_{sat} (mm/mm)	0.0288	0.0324	0.029	0.033

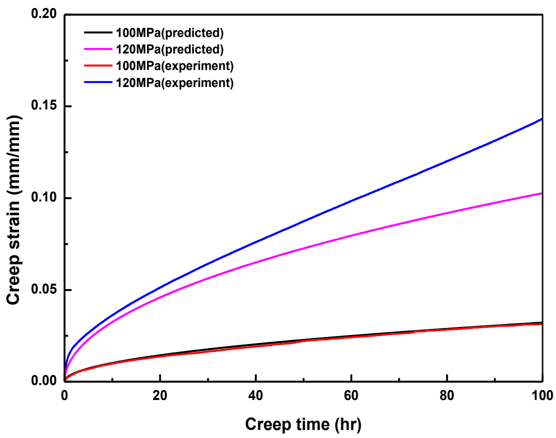

Fig. 6. Predicted creep curves

4. Conclusions

Creep behaviors of Zry-4 were predicted using stress relaxation. The stress relaxation test was conducted under tensile stresses of 65-187MPa at 400 °C. The stress relaxation results were analytically converted to the predicted creep curves. The saturated primary creep strains (ε_{sat}) were 0.029 mm/mm at 100MPa and 0.033 mm/mm at 120 MPa. The steady state creep rates ($\dot{\varepsilon}_{ss}$) were $2.48 \times 10^{-8} s^{-1}$ at 100 MPa and $2.22 \times 10^{-7} s^{-1}$at 120 MPa. The predicted creep behavior for 100 MPa coincided well with the experimental data but that for 120 MPa was not.

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