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Creep model and experimental data for CrAl-ODS-Zr alloy ATF cladding

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1. Introduction

The surface modified Zr cladding concept in KAERI has been developing as a one of the candidates for accident tolerant fuel (ATF) cladding because the corrosion/oxidation resistance and the high-temperature strength of Zr alloy. Among those, the type of the ATF cladding to be covered in this study is Zr-alloy cladding with the partially oxide dispersion strengthened (ODS) and CrAl alloy coated layer, as shown in **Fig. 1** (hereinafter denoted as CrAl-ODS-Zr alloy cladding). The effect of improving the strength of the ODS layer greatly also increased the creep resistance.

Meanwhile, the evaluation of creep deformation is essential to fuel performance analysis, because creep is one of the governing mechanisms inducing cladding deformation during the nominal LWR operation. In this regard, the development of a creep law for CrAl-ODS-Zr alloy ATF cladding was based on experimental results obtained from tests by modification of FRAPCON creep model. Also, additional creep tests for CrAl-ODS-Zry-4 ATF cladding were performed and test results were compared with modified FRAPCON creep model.

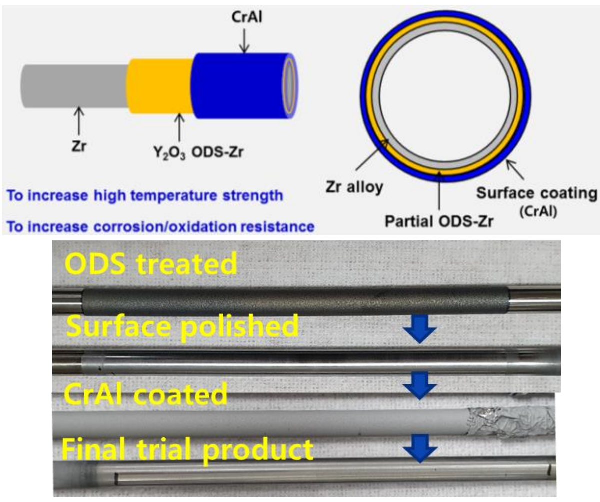

Fig. 1 Structure of CrAl-ODS-Zr alloy cladding and manufacturing process

2. Experimental

2.1 CrAl-ODS-Zr alloy ATF cladding [1]

Two technologies of outer surface coating and a partial ODS structure at the intermediated region between the outer CrAl coated layer and Zr alloy tubes are applied in this concept. In detail, the corrosion/oxidation resistance during normal operation and under accident conditions can be increased by the surface coating method (arc ion plating, AIP), and the high-temperature strength of the cladding can be increased by the partial ODS method with Y_2O_3 particles.

2.2 Creep test method [2]

Creep tests were performed in a muffle furnace using an internal pressurization method with 150-mm long specimens because this method applies the stress uniformly without a stress concentration at specific points. The creep tests were performed at 350°C and 70 to 120 MPa of hoop stress for 3800 hours. The applied hoop stress is calculated using the measured mean diameter. The assembled specimens are constantly pressurized by Ar gas to achieve the hoop stresses. The temperature was continuously monitored and maintained with an accuracy of ±4°C. The outer diameter was measured after depressurization and cooling to room temperature (RT) (**Fig. 2**). The creep strain was calculated from the average outer diameter measurement using a micrometer with a 0.0001-mm resolution. This was performed six times (axially three points and circumferentially two points per specimen), as shown in **Fig. 2**. A schematic illustration of the fixtures and test procedures for the creep test are described in **Fig. 2**.

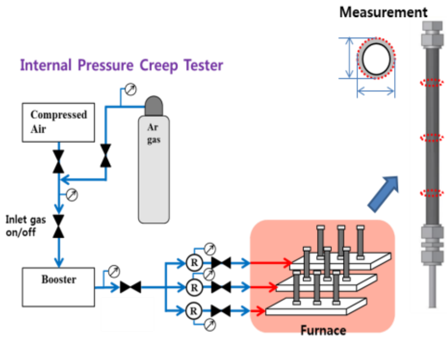

Fig. 2 Creep test method using internal pressure

3. Results and Discussion

3.1 FRAPCON creep model

The creep model in FRAPCON is based on a model given by Limbäck and Andersson (1996) [3,4]. This model uses a thermal creep model described by Matsuo (1987) and an empirical irradiation creep rate with tuned model parameters that were fit to the data set given by Franklin et al. (1983). The more details are described in **Fig. 3**. The effective stress in the cladding was used for creep calculation that is found using the principal stresses at the mid-wall radius using the thick wall formula.

Secondary rate

$$\dot{\varepsilon}_{th+irr} = \dot{\varepsilon}_{th} + \dot{\varepsilon}_{irr}$$

$$\dot{\varepsilon}_{th} = A\frac{E}{T}\left(\sinh\frac{a_i\sigma_{eff}}{E}\right)^n \exp\left(\frac{-Q}{RT}\right)$$

$$\dot{\varepsilon}_{irr} = C_0 \cdot \phi^{C_1} \cdot \sigma_{eff}^{C_2} \cdot f(T)$$

$\dot{\varepsilon}_{th}$ = thermal strain rate (in./in./hr)
$\dot{\varepsilon}_{irr}$ = irradiation strain rate (in./in./hr)
T = temperature (K)
σ_{eff} = effective stress (MPa)
R = universal gas constant (0.008314 kJ/mol-K)
ϕ = fast neutron flux (n/m^2-s)

Saturated primary strain

$$\varepsilon_p^s = 0.0216 \cdot \dot{\varepsilon}_{th+irr}^{0.109}\left(2 - \tanh\left(35500 \cdot \dot{\varepsilon}_{th+irr}\right)\right)^{-2.05}$$

Total thermal strain

$$\varepsilon_H = \varepsilon_p^s\left(1 - \exp\left(-52 \cdot \sqrt{\dot{\varepsilon}_{th+irr} \cdot t}\right)\right) + \dot{\varepsilon}_{th+irr} \cdot t$$

Primary Secondary

Total thermal strain rate

$$\dot{\varepsilon}_H = \frac{52 \cdot \varepsilon_p^s \cdot \dot{\varepsilon}_{th+irr}^{1/2}}{2 \cdot t^{1/2}} \exp\left(-52 \cdot \sqrt{\dot{\varepsilon}_{th+irr} \cdot t}\right) + \dot{\varepsilon}_{th+irr}$$

Parameter	Units	Values for SRA Cladding
A	K/MPa/hr	1.08E9
E	MPA	1.149-59.9*T
a_i	MPa^{-1}	$650\{1-0.56[1-\exp(-1.4E-27*\Phi^{1.3})]\}$ Φ = fast neutron fluence (n/cm^2)
n	unitless	2.0
Q	kJ/mole	201
R	kJ/mol-K	0.008314
C_0	$(n/m^2\text{-}s)^{-C1}$ MPa^{-C2}	4.0985E-24
C_1	unitless	0.85
C_2	unitless	1.0
f(T)	unitless	T<570K 0.7283 570<T<625K -7.0237+0.0136T T>625K 1.4763

Fig. 3 FRAPCON creep model (CREPR) [3]

3.2 Modified FRAPCON creep model for ATF cladding

For calculation of creep deformation of ATF cladding using FRAPCON creep model, the effects of main affecting parameters such as temperature and stress should be evaluated and applied. H.-G. Kim et al [5] data was used to modify FRAPCON creep model for ATF cladding because of the only existing one. **Fig. 4** shows the creep data for CrAl-ODS-Zry-4 cladding samples tested at 380°C for 1000 hours in air and at a hoop stress of 120 MPa. The amount of creep deformation of CrAl-ODS-Zry-4 cladding was greatly reduced when compared with the uncoated Zry-4. High creep resistance is mainly attributed to hard ODS layer. From this data in constant creep rate region, creep rate of 8.81966×10^{-7}/hr for CrAl-ODS-Zry-4 cladding was derived by linear approximation method as shown in **Fig. 4**. This creep rate is 11.17 times lower than that of Zry-4 estimated by FRAPCON creep model at identical condition.

It should be noted that same trend to have same effects of temperature and stress with Zr-alloys are assumed, because there is a single data at 380°C and 120 MPa of hoop stress. Therefore, the parameter "A" is modified to reflect the creep resistant effect of CrAl-ODS-Zry-4 cladding. The resulting modified FRAPCON creep model for CrAl-ODS-Zry-4 cladding shows good agreement with original creep data.

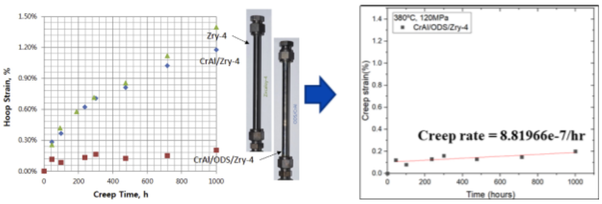

Fig. 4 Creep rate of CrAl-ODS-Zry-4 cladding at 380°C for 1000 h in air [5]

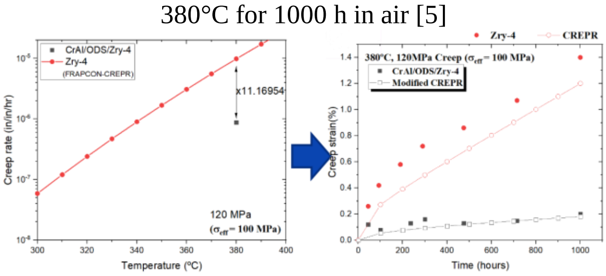

Fig. 5 Modified FRAPCON creep model for CrAl-ODS-Zry-4 cladding

3.3 Creep model assessment for ATF cladding versus experimental data

Fig. 6 shows the measured creep hoop strain of CrAl-ODS-Zry-4 cladding at 350°C as a function of time with varying hoop stress from 70 MPa to 120 MPa. For a comparative assessment, the predicted creep strain curve by modified FRAPCON creep model is also described. The CrAl-ODS-Zry-4 cladding has very small creep hoop strain, no more than tens of μm at each measurement steps. Therefore, experimentally measured data are widely scattered with large uncertainties. Nevertheless, experimental data are good agreement with the trends and magnitude of predictive curve, as shown in **Fig. 6.**

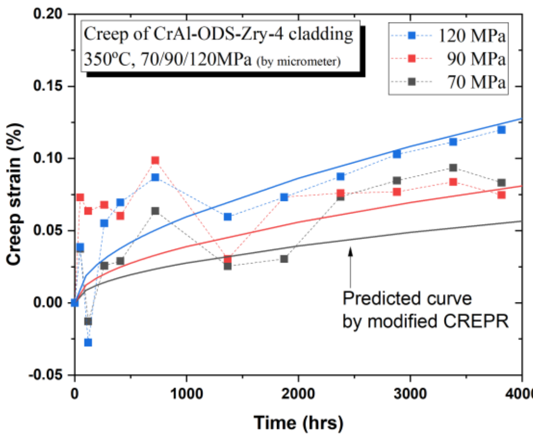

Fig. 6 Prediction curve by modified FRAPCON creep model with experimental data

It remains difficult to predict the creep behavior well due to limited available data. For a more reliable analysis, more creep data should be obtained, especially in-pile data.

3. Conclusions

To evaluate creep deformation of CrAl-ODS-Zry-4 ATF cladding, the FRAPCON creep model for Zr-alloy cladding was modified. The modifications were based on the existing experimental data. For a comparison, additional creep tests were performed and additional data are good agreement with the trends and magnitude of predictive curve, although measured data are widely scattered with large uncertainties.

Acknowledgement

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