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

Jong-Dae Hong*, Hongryul Oh, Jae Yong Kim
Korea Atomic Energy Research Institute, Daejeon, Korea
*Corresponding author: jongd@kaeri.re.kr

1. Introduction

The surface modified Zr cladding concept in KAERI has been developing as 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.

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$_2$O$_3$ 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.

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.

\[ \sigma_{\text{eff}} = \frac{1}{2} \left( \sigma_1 + \sigma_2 + \frac{3}{2} \sigma_3 \right) \]

where \( \sigma_1, \sigma_2, \sigma_3 \) are the principal stresses.

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.

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 \( 8.81966 \times 10^{-7} \text{/hr} \) 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.

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 \( 8.81966 \times 10^{-7} \text{/hr} \) 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.

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 \( 8.81966 \times 10^{-7} \text{/hr} \) 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.

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.
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-Zr-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

This work has been carried out under the Nuclear R&D Program supported by the Ministry of Science and ICT (NRF-2017M2A8A5015064).

REFERENCES

[1] J.-D. Hong, J.Y. Kim, Qualitative approach to understand fatigue behavior of CrAl-ODS-Zr alloy ATF cladding, 2021 KNS spring meeting
[3] FRAPCON 4.0, PNNL-19418 Vol.1 Rev.2