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Creep Life Prediction of Mod.HT9 Cladding for LMR

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1. Introduction

LMR fuel rod is irradiated under the high neutron flux and temperature operation conditions. Due to a lack of in-reactor stress rupture data, the stress rupture correlation is largely based upon ex-reactor furnace testing data assuming that in-and-ex-reactor behavior are similar. Designers of high temperature structures have experienced considerable success in using the life fraction technique and Larson-Miller parameter correlations to predict failure after rather complex load-time-temperature histories. We developed a creep rupture model for mod.HT9 steel based on a few experimental data made in KAERI. The results were installed into MACSIS[1] code, and the creep life prediction for EBR-II fuel rod[2] was evaluated by the MACSIS. It appears that the cumulative damage fraction(CDF) of mod.HT9 is much improved than HT9 and the design margin for metallic fuel rod is increased at same temperature.

2. Creep Life Model of Mod.HT9 Cladding

A practical method of designing for creep involves generating creep test results at relatively short times, high stresses and high temperatures. The test data can then be extrapolated to the time-temperature-stress region of interest using a parametric relationship that describes the creep behavior in terms of the variables of interest. Several parametric relationships for creep have been suggested in the literature. The Larson-Miller parameter(LMP)[3] is among the most well-known of these parametric relationships used for creep characterization of materials[4].

2.1 Life Fraction Rule

The life fraction rule considered in this study predicts that failure will occur when

$$\int_0^{t^*} \frac{dt}{t_r(\sigma,T)} = 1$$

Where t^* is the failure time and t_r is the stress-rupture life of material subjected to the engineering stress, σ, at temperature, T.

2.2 Model Description

The fact that there is an Arrhenius relation between creep rate and temperature has led to a number of time-temperature parameters to be developed which enable extrapolation and prediction of creep rates or creep rupture times to longer times than have been measured. One parameter used is the Larson-Miller parameter. This is derived by taking natural logs of the Arrhenius equation: $\dot{\varepsilon} = A\exp-(\frac{Q}{RT})$.

If we assume that the creep strain to rupture $\dot{\varepsilon}_r$ is a constant over the temperature range of interest, and the major part of the creep strain is steady state creep, then the average creep rate over the life to rupture, t_r, of the specimen is: $\dot{\varepsilon} = \varepsilon_r / t_r$. Therefore rearrangement of Arrhenius equation results in the following relationship.

$$LMP = f(\sigma) = T(C + \ln t_r) \quad (1)$$

Where C is a constant related to the constant A, and Q/R is often written as LMP, and is termed the Larson-Miller parameter.

As to the form of $f(\sigma)$ in Eq.(1), Jaske and Simonen[5] used the following equation for the HP-50 and nb-modified HP alloys:

$$LMP = f(\sigma) = C_1 + C_2 \ln\sigma + C_3(\ln\sigma)^2 + \ldots \quad (2)$$

Equations (1) and (2) can be combined to generate the following equations:

$$\ln t_r = -C^` + C_1^{'}\frac{1}{T} + C_2^{'}\frac{\ln\sigma}{T} + C_3^{'}\frac{(\ln\sigma)^2}{T} + \ldots \quad (3)$$

$$\ln t_r = -C^` + C_1^{'}X_1 + C_2^{'}X_2 + C_3^{'}X_3 + \ldots \quad (4)$$

Where $X_1 = (\ln\sigma)^{i-1}/T$ for i=1,2,.., and $C^`, C_1^{'}, C_2^{'}, C_3^{'}$ are constants to be obtained from data analysis.

2.3 Fitting Model of Mod.HT9 Steel

The least-squares method assumes that LMP follows the normal distribution, or equivalently, t_r, follows a lognormal distribution. It was used to find the parameters in (4) from accelerated life testing data[6], which is limited in higher stress(>100MPa). The multiple linear regression analysis was used to fit Eq. (3). The following is the fitted equation:

$$\ln t_r = -74.36 + 131699.6X_1 - 11412.5X_2 \quad (5)$$

Because the natural logarithm of the creep-rupture life is assumed to follow the normal distribution, the fitted Eq. (5) relates the natural logarithm of the 50^{th} percentile of the creep-rupture life to temperature and stress. We can see that the “Adjusted R Square” of the model is equal to 0.9057, pretty close to 1. This means that 90.57 percent of the variations in the creep-rupture life data can be explained by the fitted model in Eq. (5).

Because the fitting model is based on the accelerated life testing data(>100MPa) made in KAERI, the creep rupture behavior in lower stress(<100MPa), which is dominant under the steady state is not reflected. The creep rupture behavior in lower stress is extrapolated to optimum point between HT9 and ODS(Oxide Dispersion Strengthened) steel model so that adjusted R square value close to unity. The material constant through the multiple linear regression analysis and the following is the fitted equation:

$$\log t_r = -21.6404 + \frac{34287.045}{T_c + 273.2} - \frac{5540.379}{T_c + 273.2}\log\sigma$$

$$LMP = (T_c + 273.2)(21.64 + \log t_r) \quad (6)$$

$$= 34287.045 - 5540.379\log\sigma$$

As the figure 1 shows, the model is in agreement with the rupture data at 650℃ and has the higher creep rupture resistance than HT9, the lower than ODS at the same temperature. Also the relationship for Larson-Miller parameter and experimental data is shown in figure 2. Due to the lower stress extrapolation, the error for data slightly increased.

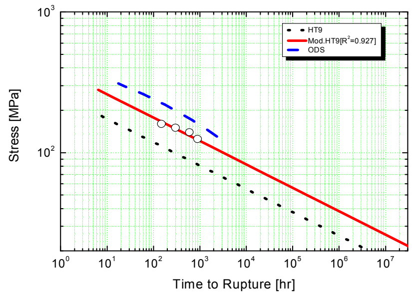

Figure 1. Mod.HT9/HT9/ODS Rupture Model

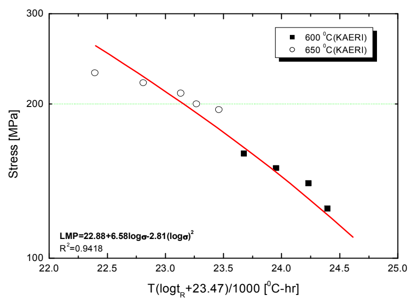

Figure 2. Mod.HT9/HT9/ODS Rupture Model

3. Evaluation on creep life of Mod.HT9 steel

Creep rupture for Mod.HT9 steel was modeled for MACSIS. Because the model correlated based on a few experimental data limited at > 100MPa, it was extrapolated at lower stress(<100MPa) between HT9 and ODS steel. The results were installed into MACSIS code, and the CDF for EBR-II fuel rod which is irradiated with U-10Zr type and 46.7 kW/m peak linear heat generation rate was evaluated by the MACSIS.

Figure 3 shows CDF on HT9 and Mod.HT9 predicted by life fraction rule. As the burnup increases, CDF of mod.HT9 is much lower than that of HT9 steel as well as design limit(<0.001).

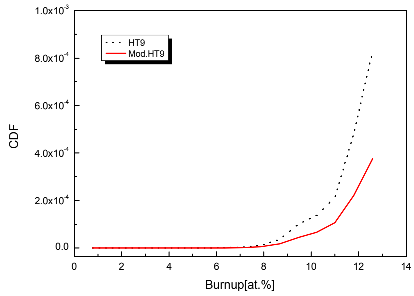

Figure 3. Mod.HT9/HT9/ODS Rupture Model

Hoop stress for HT9 and mod.HT9 is 63.4, 59MPa respectively. It is thought that these results are conservative than realistic phenomenon because modeling is based on >100MPa.

4. Conclusion

As the core outlet temperature is increased from 530℃ to 545℃ based on KALIMER-600 design concepts, the integrity of the HT9 cladding having low long term creep strength at high temperature is not guaranteed. In this paper creep rupture for mod.HT9 steel were modeled and installed into MACSIS code, and the creep life for irradiated fuel rod was evaluated. The mod.HT9 steel showed the higher creep rupture resistance than that of HT9 cladding at the same temperature. It appeared that mod.HT9 steel has a good potential that can replace HT9 steel as the metallic fuel cladding for LMR.

Acknowledgement

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