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Evaluation on Creep properties of the modified HT9-W Fuel Rod According to the Variations of Temperature and Burnup

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1. Introduction

LMR fuel rod is irradiated under the high neutron flux and temperature operation conditions. Moreover 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. The parameters affected on fuel rod deformation are fission gas release, rod pressure build-up, FCMI, and cladding creep on at the high pressure and temperature under long term operation condition. One of the most important factors among these parameters is cladding creep phenomenon due to gas pressure build-up within the fuel rod[1]. In-reactor thermal and irradiation creep characteristics for modified HT9-W were analyzed, and these characteristics were modeled for MACSIS[2] in this study. The results were installed into MACSIS code, and the creep deformation for EBR-II fuel rod[3] was evaluated by the MACSIS. It appears that the thermal creep resistance of the modified HT9-W is improved than HT9 and the design margin for metallic fuel rod is increased at high temperature.

2. Creep of the modified HT9-W cladding

In this section some of the creep models for the modified HT9-W cladding are described. The creep model includes the thermal creep and irradiation models.

2.1 Thermal Creep Model

Although creep can occur at any temperature, only at temperatures exceeding about 0.4 of the melting point of the material are the full range of effects visible($T \geq 0.4T_M$). At lower temperatures, creep is generally characterized by an ever-decreasing strain rate, while at elevated temperature, creep usually proceeds through three distinct stages and ultimately results in failure. Because the material generally gets along most of life at steady state stage, creep rate at this stage is very important factor affected the life of the material[1]. As the experimental creep rate datas for the modified HT9-W steel scarcely are published, only a few minimum creep rates[4] for the modified HT9-W which is the slope of the portion of the creep vs. time corresponding to secondary creep and has a high activation energy than HT9 is used to determine the optimum activation energy for the modified HT9-W at second stage based on the HT9 model. The model due to the optimum activation energy is given by;

$$\dot{\bar{\varepsilon}}_T = \dot{\bar{\varepsilon}}_{TP}(primary) + \dot{\bar{\varepsilon}}_{TS}(steady-state) + \dot{\bar{\varepsilon}}_{TT}(tertiary)$$

$$\dot{\bar{\varepsilon}}_{TP} = \left[C_1 \exp(-\frac{Q_1}{RT})\bar{\sigma} + C_2 \exp(-\frac{Q_2}{RT})\bar{\sigma}^4 + C_3 \exp(-\frac{Q_3}{RT})\bar{\sigma}^{0.5}\right] \times C_4 \exp[-C_4 t]$$

$$\dot{\bar{\varepsilon}}_{TS} = \left[C_5 \exp(-\frac{Q_4}{RT})\bar{\sigma}^2 + C_6 \exp(-\frac{Q_5}{RT})\bar{\sigma}^5\right]$$

$$\dot{\bar{\varepsilon}}_{TS} = \left[4C_7 \exp(-\frac{Q_6}{RT})\bar{\sigma}^{10}\right] t^3$$

$\dot{\bar{\varepsilon}}_T$ = effective thermal creep strain rate, %
R = gas constant, 1.987
$\bar{\sigma}$ = effective stress, Mpa
$C_1 = 13.4$, $C_2 = 8.43\times10^{-3}$, $C_3 = 4.08\times10^{18}$
$C_4 = 1.6\times10^{-6}$, $C_5 = 3.49\times10^{8}$, $C_6 = 4.51\times10^{8}$,
$C_7 = 9.53\times10^{18}$, $Q_1 = 15027$, $Q_2 = 26451$,
$Q_3 = 89167$, $Q_4 = 109100$, $Q_5 = 115200$, $Q_6 = 282700$

As the figure 1 shows, the model which is in agreement with the minimum creep rate of reference 4 has the higher creep resistance than HT9 at the same temperature and stress according to the variation of time. As the applied stress increases, the creep of the modified HT9-W model increases at higher temperature(see figure 2).

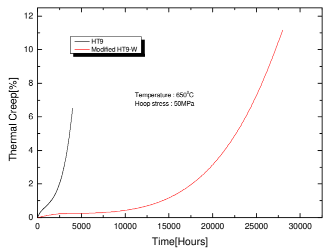

Figure 1. The thermal creep model for HT9, modified HT9-W with time

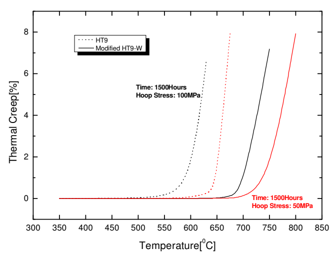

Figure 2. Comparison of the thermal creep model for HT9 and modified HT9-W with temperature

2.2 Irradiation Creep Model

As the irradiation induced creep data for the modified HT9-W don't exist, the HT9 model[3] having a similar property is used.

The purely irradiation-induced creep is represented as $\dot{\varepsilon}_I$ and has the form,

$$\dot{\varepsilon}_I = \left[B_0 + A\exp(-\frac{Q}{RT}) \right] \Phi \bar{\sigma}^{1.3} \times 10^{-7}$$

$\dot{\varepsilon}_I =$ *effective strain rate, %*

$\bar{\sigma} =$ *effective stress, MPa*

$B_0 = 1.83 \times 10^{-4}$

$\Phi =$ *neutron fluence* 10^{22} $n/cm^2 (E > 0.1 MeV)$

$A = 2.59 \times 10^{14}$

$Q = 73000$

$T =$ *temperature, K*

$R = 1.987$

3. Evaluation on creep properties of the modified HT9-W steel

Creep characteristics for modified HT9-W were modeled for MACSIS. The results were installed into MACSIS code, and the creep deformation for EBR-II fuel rod(T225)[5] 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 the thermal creep strain on HT9 and modified HT9-W with inlet temperature(360~450℃) and burnup. As the inlet temperature increases, the difference of the creep strain for HT9 and modified HT9-W rod decreases but modified HT9-W fuel rod predicts the lower thermal creep strain than HT9 fuel rod.

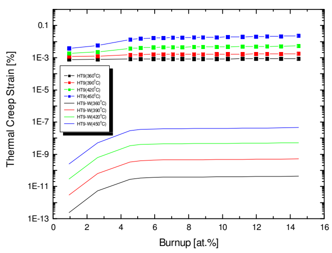

Figure 3. thermal creep strain on HT9 and modified HT9-W with burnup

Also total creep strain on HT9 and modified HT9-W rod shows in figure 4. Since the same model on the irradiation creep is applied, only thermal creep dominates in total creep deformation. As the inlet temperature increases, the creep resistance of the modified HT9-W cladding is higher than that of HT9 cladding.

Therefore the modified HT9-W steel has more design margin for fuel rod integrity at high temperature and has a good potential for the metallic fuel cladding for KALIMER-600.

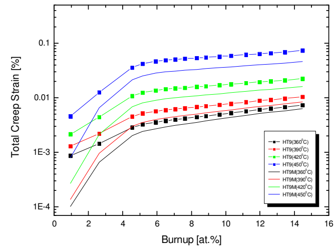

Figure 4. total creep strain on HT9 and modified HT9-W with burnup

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 for modified HT9-W steel were modeled and installed into MACSIS code, and the creep for irradiated fuel rod was evaluated. The modified HT9-W steel showed the higher creep resistance than that of HT9 cladding at high temperature. It appeared that modified HT9-W steel which improves on creep resistance at high temperature has good potential that can replace HT9 steel as the metallic fuel cladding for LMR.

Acknowledgement

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