Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 29-30, 2014

Modelling of U-Mo/Al dispersion fuel fission induced swelling and creep

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1. Introduction

Fission induced creep and swelling of U-Mo alloy and aluminum (Al) alloy cladding monolithic fuel has been investigated previously [1]. In a monolithic fuel plate, it was observed that U-Mo fuel creep and fuel mass transfer from the transverse end of the meat edge where the fission density is the highest, to the transverse center so that bulged region was formed between the meat edge and transverse center. It has been explained by fission-induced creep of the fuel under the stress from fission product swelling.

In a dispersion fuel which U-Mo particles are dispersed in Al metal matrix, a similar phenomenon forming a bulge region was observed but it is difficult to quantify and construct a model for explaining creep and swelling because of its complex microstructure change during irradiation including interaction layer (IL) and porosity formation.

In a dispersion fuel meat, fission product induces fuel particles swelling and it has to be accommodated by the deformation of the Al matrix and newly formed IL during irradiation. Then, it is reasonable that stress from fuel swelling in the complex structure should be relaxed by local adjustments of particles, Al matrix, and IL.

For analysis of U-Mo/Al dispersion fuel creep, the creep of U-Mo particle, Al matrix, and IL should be considered. Moreover, not only fuel particle swelling and IL growth, but also fuel and Al matrix consumptions due to IL formation are accounted in terms of their volume fraction changes during irradiation.

In this work, fuel particles, Al matrix and IL are treated in a way of homogenized constituents: Fuel particles, Al matrix and IL consist of an equivalent meat during irradiation. Meat volume swelling of two representative plates was measured: One (Plate A) was a pure Al matrix with 6g/cc uranium loading, the other (Plate B) a silicon added Al matrix with 8g/cc uranium loading. The meat swelling was calculated as a function of burnup. The meat swelling of calculation and measurement was compared and the creep rate coefficients for Al and IL were estimated by repetitions.

Based on assumption that only the continuous phase of Al-IL combined matrix accommodated the stress from fuel particle swelling and it was allowed to have creep deformation, the homogenization modeling was performed.

2. Experimental Method

Optical microscopy images of plate A and plate B are shown in Fig. 1 and fuel swelling can be identified by the plate thickness increasing. Since plate A had a symmetric power in plate width direction and plate B did a higher power at the one of sides, the images shown in the Fig. 1 is of a particle cross section for A and of the whole width for B.

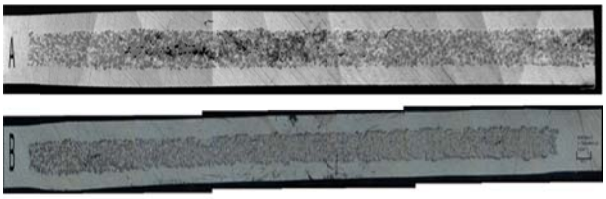

Fig. 1 Optical microscopy images of plate A and B cross sections at axial center.

The measured meat swelling can be obtained by using as-fabricated meat thickness and meat thickness changes as follows:

$$\left(\frac{\Delta V}{V_0}\right)_m = \frac{\Delta t_m}{t^0{}_m} \qquad (1)$$

where Δt_m is the meat thickness change before and after irradiation, $t^0{}_m$ the as-fabricated meat thickness. The meat thickness was measured at every 0.5 mm in the width direction. Porosity was measured at the same locations of meat thickness measurement. The meat swelling was then corrected by subtracting the porosity from measured meat swelling since porosity was not considered in the homogenization model.

3. Meat Swelling Modeling

The fuel meat volume in dispersion fuel changes by fuel particle swelling by fission product, IL growth, and fuel and Al matrix consumption caused by IL formation during irradiation. The total meat swelling considering mentioned factors can be expressed as follows:

$$\left(\frac{\Delta V}{V_0}\right)_m = \frac{v_{f,0}\left(\frac{\Delta V}{V_0}\right)_f + \frac{V_{IL}}{V_m} - v_{f,0}\left(\frac{\Delta V}{V_0}\right)_{f,c} - v_{Al,0}\left(\frac{\Delta V}{V_0}\right)_{Al,c}}{\left[1-\frac{V_{IL}}{V_m}\right]} \qquad (2)$$

where $v_{f,0}$,$v_{Al,0}$ is the as-fabricated fuel and Al volume fraction respectively, $\frac{V_{IL}}{V_m}$ the IL volume fraction in the meat, $(\frac{\Delta V}{V_0})_f$ the fuel swelling by fission product , $(\frac{\Delta V}{V_0})_{f,c}$, $(\frac{\Delta V}{V_0})_{Al,c}$ the fuel and Al volume fraction consumed by IL growth respectively. $(\frac{\Delta V}{V_0})_f$, fuel particle swelling for U-Mo fuel alloy below 250℃ was well defined previously [3] given fission density. Then, Eq. (2) contains three unknowns, : $\frac{V_{IL}}{V_m}$, $\left(\frac{\Delta V}{V_0}\right)_{f,c}$, $\left(\frac{\Delta V}{V_0}\right)_{Al,c}$ and they can be iteratively found when power history and irradiation temperature are given.

4. ABAQUS Simulation

Fission induced creep of U-Mo alloy is of dependence on the applied stress and fission rate [2]. Since the temperature regime of interest is so low, thermal creep was not considered in this dispersion case. Like monolithic case [1], the fission induced creep rate is linearly proportional to the fission rate. Thus, the homogenized meat creep rate in the dispersion fuel can be expressed as follows:

$$\dot{\boldsymbol{\varepsilon}}_c = \mathbf{A}_{meat}\boldsymbol{\sigma}\dot{\boldsymbol{f}} \qquad (3)$$

where $\dot{\varepsilon}_c$ is the equivalent creep strain rate (s^{-1}), A_{meat} the creep rate coefficient of the meat, σ the equivalent stress(MPa), and $\dot{f}$ the fission rate ($fissions/cm^3$-s).

For a typical U-Mo/Al dispersion fuel of which fuel volume fraction is smaller than that of Al matrix, the Al matrix and IL combined are continuous phase with isolated U-Mo fuel particles. Thus, it means that the Al matrix and IL combined play a role of local adjustment for relaxing complex stress state due to fission induced fuel swelling while the fuel particles remain inactive during irradiation. In homogenization model, the Al matrix and IL combined are supposed to comprise of a single continuous phase by averaging each creep rate coefficient of Al matrix and IL for creep increment. The creep rate coefficient of meat, A_{meat}, in Eq. (3) can be given as follows :

$$\mathbf{A}_{meat} = \boldsymbol{v}_{IL}\boldsymbol{A}_{IL} + \boldsymbol{v}_{Al}\boldsymbol{A}_{Al} \qquad (4)$$

where v_{IL}, v_{Al} are the volume fraction of IL and Al matrix, and A_{IL}, A_{Al} the creep rate coefficient of IL and Al matrix during irradiation respectively.

Two plates were irradiated with edge-on loading and had the same cladding thickness on both faces. For two plates, only the upper half of the fuel plate was modeled with consideration for their symmetry. A schematic of fuel plate cross section and FEA modeling scheme are presented in Fig. 2.

Meat true strains is derived from meat swelling given in Eq. (2) as follow :

$$\boldsymbol{\varepsilon}_{sw,true} = \mathbf{ln}(\mathbf{1} + \left(\frac{\Delta V}{V_0}\right)_{\boldsymbol{m}}) \qquad (5)$$

where $\varepsilon_{sw,true}$ is the swelling strain of the meat and $\left(\frac{\Delta V}{V_0}\right)_m$ the meat swelling calculated from Eq.(2).

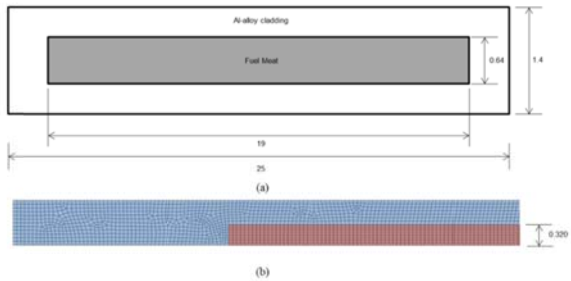

Fig. 2 Finite element modeling for plate A and B with edge-on loading and symmetric cladding thickness. (a) Schematic of fuel plate cross section and (b) finite element modeling.

Table **1** summarizes material properties and calculation scheme for creep and swelling in ABAQUS simulation.

Table 1. Summary of material properties and calculation scheme used in ABAQUS simulation.

	Al 6061 Cladding	**U-Mo Fuel particle**	**Reference**
Poisson's ratio	0.34	0.34	[1]
Young's modulus	66GPa	85GPa	[1]
Yield strength	Increasing ~280Mpa due to irradiation hardening	-	[1]
Creep rate for meat	$\dot{\varepsilon}_c = A_{meat}\sigma\dot{f}$		[2]
Swelling increment for meat	$\varepsilon_{sw,true} = \ln(1 + \left(\frac{\Delta V}{V_0}\right)_m)$		[1]

The ABAQUS simulation results for plate A and B are shown in Fig. 3. The calculated meat swelling without creep by using Eq. (2) is also provided for comparison. The best fit results were obtained when the creep rate coefficient for Al matrix and for IL were

$100 \times 10^{-25} cm^3 \mathrm{MPa}^{-1}$ and $250 \times 10^{-25} cm^3 \mathrm{MPa}^{-1}$ for two plates.

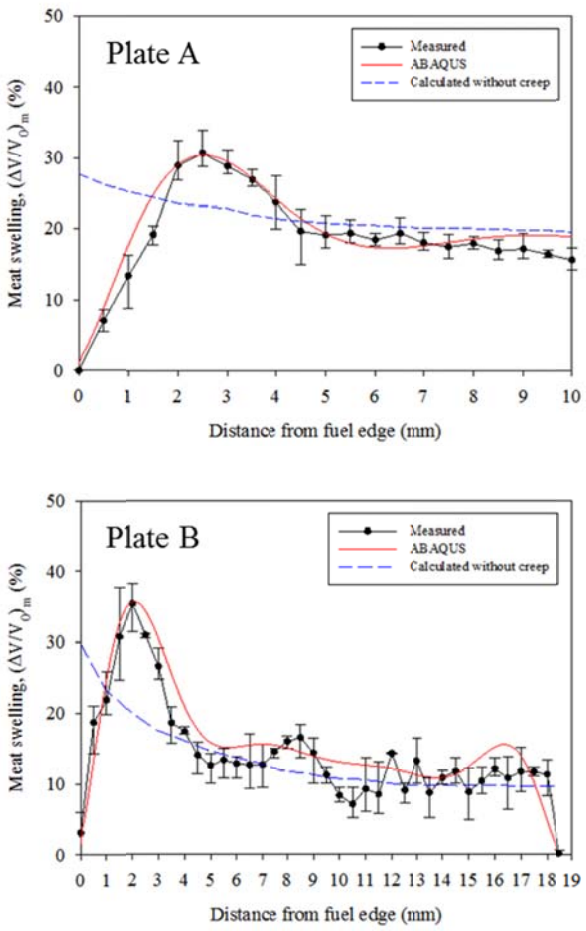

Fig. 3 ABAQUS simulation results for meat swelling of plate A and B. Measured and calculated meat swelling without creep were provided for comparison. The best fit results were obtained when the creep rate coefficients of Al matrix and IL were $\mathbf{100 \times 10^{-25} cm^3 MPa^{-1}}$ and $\mathbf{250 \times 10^{-25} cm^3 MPa^{-1}}$ respectively.

Considering that the creep rate coefficient of U-Mo alloy was $500 \times 10^{-25} cm^3 \mathrm{MPa}^{-1}$ [1], the result that creep rate coefficient of IL is $250 \times 10^{-25} cm^3 \mathrm{MPa}^{-1}$ is not reasonable since IL becomes amorphous with a low viscosity which should lead to much higher creep rate coefficient. Therefore, the obtained creep rate coefficients of Al matrix and IL are considered to be effective fit values for the measured results.

5. Conclusions

The meat swelling of two U-Mo/Al dispersion fuel plates was modeled by using homogenization model. One (Plate A) with a pure Al matrix, the other (Plate B) with a silicon added Al matrix. Fuel particle, Al matrix and IL were treated in a manner of homogenized constituents so that not only fuel swelling by fission product and IL growth, but also volume consumption of Al matrix and fuel due to IL formation were considered simultaneously.

The meat swelling of calculation and measurement was compared and the creep rate coefficients for Al and IL were estimated by using ABAQUS simulation. The coefficients of Al matrix and IL for best fit were $100 \times 10^{-25} cm^3 \mathrm{MPa}^{-1}$ and $250 \times 10^{-25} cm^3 \mathrm{MPa}^{-1}$ respectively. These creep rate coefficients are effective value for fitting to the measured meat swelling. Therefore, further studies and simulations considering how the presence of U-Mo fuel particles influence on meat swelling and creep should be necessary.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Education, Science and Technology) (No. 2011-0031771)

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