Fuel Performance Modeling of U-Mo Dispersion Fuel: The thermal conductivity of the interaction layers of the irradiated U-Mo dispersion fuel

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1. Introduction

U-Mo/Al dispersion fuel is a promising candidate for the research reactor fuel due to its high U loading and high thermal conductivity. U-Mo/Al dispersion fuel performed well at a low burn-up. However, higher burn-up and higher fission rate irradiation testing showed enhanced fuel meat swelling which was caused by high interaction layer growth and pore formation [1,2].

The performance of the dispersion type fuel in the irradiation and un-irradiation environment is very important. During the fabrication of the dispersion type fuel an Interaction Layer (IL) is formed due to the inter-diffusion between the U-Mo fuel particles and the Al matrix which is an intermetallic compound (U,Mo)Al_x [3]. During irradiation, the IL becomes amorphous causing a further decrease in the thermal conductivity and an increase in the centerline temperature of the fuel meat [4]. Several analytical models [5-6] and numerical methods [7] were developed to study the performance of the un-irradiated U-Mo/Al dispersion fuel. Two analytical models were developed to study the performance of the irradiated U-Mo/Al dispersion fuel. In these models [8,9], the thermal conductivity of the IL was assumed to be constant. The properties of the irradiated U-Mo dispersion fuel have been investigated recently by Huber et al. [10]

The objective of this study is to develop a correlation for IL thermal conductivity during irradiation as a function of the temperature and fission density from the experimentally measured thermal conductivity of the irradiated U-Mo/Al dispersion fuel.

2. Review of experiments

Idaho National Laboratory conducted the Advanced Test Reactor (ATR) Full-size plate In Center Flux Trap Position (AFIP-1 test) with U-Mo/Al-Si dispersion fuel. Burkes et al measured the thermal conductivity of the two segments of irradiated AFIP-1 fuel plates [6,9]. One segment was irradiated up to a low burn-up (referred as TL) and the other segment was irradiated up to a high burn-up (referred as TK). Table-1 shows the characteristics of the two segments measured by Burkes et al [6,9].

Table 1: Characteristics of irradiated fuel segments

	TL	TK	As-fabricated
Fuel particle fission density (10^{21} f/cm^3)	4.86	6.12	0
Vol. % of fuel particle	50.9	49.1	53.9
Vol. % of IL	35.8	50.9	0
IL thickness (µm)	5.76	7.66	0

The average fuel particle radius was 33.5 µm. The IL thickness was measured by assuming that the IL consumes only the matrix (i.e. the fuel particle radius is constant) using the volume fraction change of the fuel matrix before and after irradiation according to the following equation [10]:

$$R = r\sqrt[3]{\frac{V_{m,i} - 1}{V_{m,0} - 1}} \qquad (1)$$

The experimentally measured thermal conductivities for the two segments are shown in Table 2 [10].

Table 2: experimentally measured thermal conductivity

Temperature (°C)	Thermal conductivity	
	TL	TK
25	7.15744	13.6557
50	7.85849	14.63025
75	8.11272	15.5239
100	8.47481	16.57934
150	8.92164	17.14943
200	9.22209	17.7606
250	10.07722	18.60547
300	10.83991	19.7418

3. IL thermal conductivity

Several models have been developed to study the thermal conductivity of composite materials, and Maxwell's model is the basis for them. Maxwell's [11] model is developed only for the low volume fraction of spherical fuel particles distributed homogenously in the matrix. Hsu et al [12] (equation 2) developed a model for an infinite number of dispersed particles. Sevostianov and

Kachanov [13] developed a model for the thermal conductivity of the coated particles dispersed in a matrix by finding the thermal conductivity for equivalent homogenous inclusion to a fuel particle of radius r and IL of thickness h as shown in equation 3.

$$\{1-\mathrm{F(e)}\}\lambda_e^2+\{\lambda_d[\mathrm{F(e)}-v_d]+\lambda_m[\mathrm{F(e)}-v_m]\}\lambda_e-\lambda_m\lambda_d\mathrm{F(e)}=0 \quad (2)$$

$$\lambda_p=\lambda_i\frac{2+\left(1+\frac{Y}{r}\right)^3\times\left(2\frac{\lambda_i}{\lambda_f}+1\right)/\left(1-\frac{\lambda_i}{\lambda_f}\right)}{\left(1+\frac{Y}{r}\right)^3\times\left(2\frac{\lambda_i}{\lambda_f}+1\right)/\left(1-\frac{\lambda_i}{\lambda_f}\right)-1} \quad (3)$$

$$\lambda_{U-Mo}(T_m,f)=1.294\times10^{-5}\times T_m^2-5.59\times10^{-3}\times T_m^2\times f-1.46\times10^{-5}\times f^2+4.11\times10^{-2}\times T_m-0.741\times f+10.8 \quad (4)$$

$$\lambda_{Al-xSi}(T_m,f)=-0.478*x^3+0.702*10^{-3}*x^2*T_m-50.8*10^{-6}*x*T_m^2-0.507\times10^{-6}\times T_m^3+6.64*x^2-28.2*10^{-3}*x*T_m-387\times10^{-6}\times T_m^3 \quad (5)$$

$$\lambda_{IL}=23.262+0.188\times T-5.9\times10^{-4}T^2-(2.465+2.632\times10^{-2}T-9.37\times10^{-5}T^2)f \quad (6)$$

where $F(e)$ is the shape factor and it is equal to 1/3 for spherical particles, λ is the thermal conductivity. i , f, m, p, d, and e stand for the IL, U-Mo alloy, matrix, fuel particle (U-Mo alloy and the IL), dispersed particle, and the effective thermal conductivity of the composite respectively. T is the temperature in ^{o}C and f is the fuel particle fission density in 10^{21} f/cm^3.

The microstructure of the U-Mo/Al dispersion fuel is composed of U-Mo fuel particles surrounded by an interaction layer which together are uniformly dispersed in the Al matrix. For the TK sample, the matrix was totally consumed by the IL. Therefore, Hsu's model was used to calculate the thermal conductivity for IL from the experimentally measured thermal conductivity of the U-Mo/Al dispersion fuel (Table 1) and the U-Mo alloy (equation 4). For TL sample, the thermal conductivity of the fuel particle was firstly calculated by Hsu's model using the thermal conductivity of Al-2 wt.% Si matrix (equation 5) and then the thermal conductivity of the IL was calculated using the thermal conductivity of the U-Mo alloy from equation 3.

4. Results and discussion

The thermal conductivity of the IL for the two fuel segments is shown in Fig. 1. As can be seen from Fig. 1, the thermal conductivity of the IL increases with temperature and decreases with the fission density.

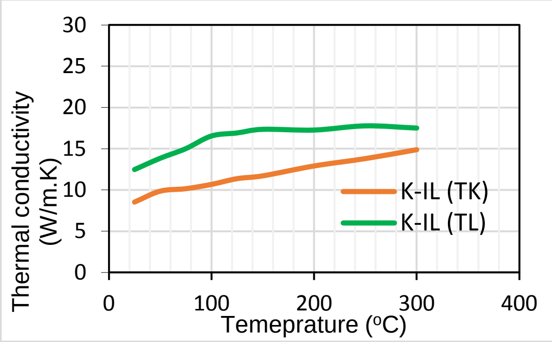

Fig. 1. The thermal conductivity of the IL for the two fuel segments of U-Mo/Al-Si dispersion fuel

The thermal conductivity of the IL for TL segment was between 12-18 W/m-K and 8-15 for TK segment. Ryu et al. assumed the thermal conductivity of the IL to be constant (10 W/m-K) [8] and Burkes assumed the thermal conductivity of the IL to be independent of the fission density and equal to the un-irradiated U-Mo alloy thermal conductivity which contradicts the experimentally measured thermal conductivity of the IL.

A correlation was developed for the thermal conductivity of IL as a function of temperature and fission density by fitting the experimentally measured data (equation 6).

5. Conclusions

The thermal conductivity of IL during irradiation was calculated from the experimentally measured data and a correlation was developed from the thermal conductivity of IL as a function of T and fission density. Previous models developed to predict the performance of U-Mo/Al dispersion fuel assumed the IL thermal conductivity to be independent of the fission density. Therefore, a new model needs to be developed based on the newly measured IL thermal conductivity.

Acknowledgments

This study was supported by Ministry of Science, Information and Future Planning (NRF-2015M2C1A1027541) and by the KUSTAR-KAIST Institute, KAIST.

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