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Influence of Fuel-Matrix Interaction on the Deformation of U-Mo Dispersion Fuel

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1. Introduction

U-Mo dispersion fuel has been investigated for the future use in high performance research reactors. In order to demonstrate the fuel performance of U-Mo fuel, a series of irradiation tests are has been conducted worldwide [1]. Diffusion reaction between the U-Mo fuel particles and the Al matrix during irradiation has been one of the fuel performance limiting issues because interaction layer (IL) formation induces fuel performance degradation [2]. Moreover, excessive volume expansion of the fuel plate caused by breakaway swelling of the fuel meat occurs by the development of the porosity at the interface of the IL and Al matrix [3].

In order to predict the fuel plate failure leading to breakaway swelling in the meat, an understanding of the effects of the fuel-matrix interaction behavior on the deformation of fuel meat is necessary. However, the effects of IL formation on the development of breakaway swelling have not been studied thoroughly. A mechanism that explains large pore growth that leads to breakaway swelling has not been included in the existing fuel performance models [4].

In this study, the effect of the fuel-matrix interaction on large interfacial porosity development at the IL-Al interface is analyzed using both mechanistic correlations and observations from the post-irradiation examination results of U-Mo dispersion fuels.

2. Methods and Results

The yields of gaseous fission products including Xe and Kr are known to be approximately 0.26 per fission. Therefore, the number of moles of fission gas atoms can be obtained as a function of U-235 burnup. The fission gas atoms are produced at a rate of $4.3\text{x}10^{-27}$ moles of gases per percent FIHMA. There are $3.7\text{x}10^{22}$ atoms of uranium per cubic centimeter of U-7wt%Mo. Therefore, the number of moles of gas atoms formed per cubic centimeter of U-7Mo per percent FIHMA is $1.6 \text{ x } 10^{-4}$.

The pressure of gases in a pore can be calculated by using the ideal gas law:

$$\mathrm{P}_{ip} = \frac{n_{FGR}RT}{V_{ip}} \qquad (1)$$

where P_{ip} is the pressure in the interfacial pores, n_{FGR} is the number of moles of gas contained in the interfacial pore, R is the gas constant (8.314 J/mol-K), T is the fuel temperature in K, and V_{ip} is the volume of the interfacial pore. For the UO_2/Stainless Steel dispersion fuel, the volume of the interfacial pores was calculated by using the fabrication porosity of UO_2. The fabrication porosity might vary in a range 2 - 10 vol.% in U-Mo/Al dispersion fuel, depending on the fuel particle loading and fuel particle shape. Although the interfacial pore forms after a certain incubation period during which enough fission gas atoms need to accumulate at the IL-Al interface [5], the volume fraction of the interfacial pore was set to 2 vol.% from the beginning for a simpler estimate for the fission gas pressure, based on typical as-fabrication porosity.

Fission gas release from U-Mo fuel particles to the IL-Al interface is by diffusional release and direct recoil. The diffusion part of fission gas release from fuel particles can be expressed by the Booth's model as follows [6]:

$$f_D = \frac{4}{a_s}\sqrt{\frac{Dt}{\pi}} \qquad (2)$$

where f_D is the fraction of fission products released by diffusion, D is the diffusion constant, t is time, and a_s is the radius of an equivalent sphere. The recoil part of gas release can be expressed by the following equation [7]:

$$f_R = \frac{3}{4}\left(\frac{R}{a}\right) - \frac{1}{16}\left(\frac{R}{a}\right)^3 \qquad (3)$$

where f_R is the fraction of fission gases that are released by recoil, R is the recoil range, and a is the radius of the fuel particle. In the present modeling, we assume that all of the fission gas atoms that recoil out of fuel particles are eventually transported to the IL-Al interface. The recoil ranges in uranium and aluminum for fission gas atoms with a most probable energy are 6.8 μm and 13.7 μm, respectively [8]. In addition, we also assume that all fission gases in the ILs are released readily to the large IL-Al interfacial pores. The fission gas release to the IL-Al interfacial pores increases with the IL thickness.

One of the most significant microstructural changes attributed to severe interaction is the consumption of the Al matrix. As the volume fraction of the Al matrix decreases, the fission gas pores at the IL-Al interface are more likely to be connected each other, and the mechanical constraints required to keep the dimensional robustness of the fuel plates become loose. The fission gas atoms released to the IL-Al interfaces start to affect the deformation of the matrix, which leads to breakaway swelling of the U-Mo/Al fuel plate when the ILs grow and consume the Al matrix. Consequently, a high as-fabricated fuel loading presents a more vulnerable condition for breakaway swelling. The inter-particle distance decreases as the loading of U-Mo particles rises and the mechanical constraint of the matrix may fall below the minimum at a lower burnup. The stress of the Al matrix in an equilibrium with a pore having a certain pressure can be estimated by using a modified hollow sphere model, invoking classical solid mechanics [9]:

$$\mathrm{P}_y = \frac{2}{3} S_y \ln \frac{1}{1-V_m} \tag{4}$$

where P_y is the gas pressure to yield the shell of a hollow sphere, S_y is the yield strength of the matrix, V_m is the volume fraction of the matrix. The yielding of the matrix is considered a criterion to initiate breakaway swelling in this model because cracks may eventuate from the yielding of the matrix and then they will lead to breakaway swelling of a dispersion fuel plate.

The distance between U-Mo particles can be simplified by assuming a close-packing array of spherical particles of uniform size as follows:

$$\mathrm{d} = \left[\left(\frac{\pi}{3\sqrt{2} V_f} \right)^{1/3} - 1 \right] \cdot D \tag{5}$$

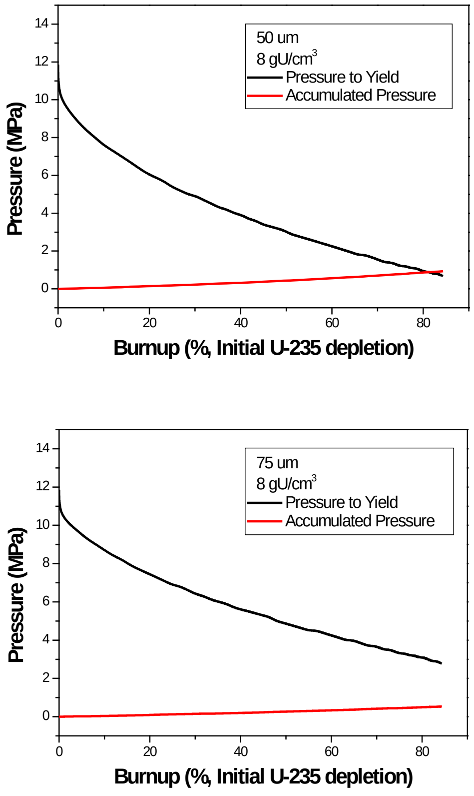
where D is the fuel particle size, and V_f is the volume fraction of the fuel particles. In this model, it is worth noticing that the distance between fuel particles d increases linearly with the fuel particle size D. When we take 50 vol.% fuel particle loading (V_f=0.5) for example, d is approximately 0.14D. For a typical fuel particle size of 70 μm, d ~10 μm, which means that if ILs with thickness of 0.07D, or ~5 μm, ILs start to contact each other. However, if the fuel particle size increases to 140 μm, the corresponding IL thickness to make contact with the closest IL becomes double.

The remaining volume fraction of the Al matrix can be calculated as follows:

$$V_m = 1 - V_f \left(1 + \frac{1}{D/2L_m} \right)^3 \tag{6}$$

where V_m is the remaining volume fraction of the Al matrix, and L_m is the partial IL thickness that corresponds to the consumed Al thickness. The limitation of the close-packing assumption might be that it cannot estimate the volume fractions of consumed and remaining Al matrix once the ILs of neighboring particles starts to make contact with each other. In addition, the IL also consumes the fuel particle and the rate of consumption is a function of the stoichiometry of the IL, which in turn is a function of irradiation condition. Therefore, a realistic calculation beyond the point of the IL connection should rely on fuel performance codes [4].

For the model calculation of IL growth of plate-type U-Mo dispersion fuel, the irradiation data such as heat flux, fission density, cladding surface temperature, U-235 burnup and test duration for the AFIP-1 test available in the open literature were used in this study [10]. The pressure to yield the Al matrix and the accumulated fission gas pressure in the pore at the IL-Al interface were calculated as shown in Fig. 1. When the U-Mo particles for a fuel loading of 8 g-U/cm^3 has the average U-Mo particle size of 50 μm, the fission gas pressure in the pore becomes higher than the pressure to yield the Al matrix shortly before end-of-life (EOL), which is, as we define, a prediction for breakaway swelling. However, when a larger U-Mo size of 75 μm was used with the same fuel loading, the pore pressure remains lower than the pressure to yield the Al matrix for life.



(a)

(b)

Fig. 1. Comparison of the pressure to yield and the accumulated pressure for dispersion fuels (a) with 50 μm fuel particles and (b) with 75 μm fuel particles irradiated under AFIP-1 conditions[10].

3. Conclusions

The effects of fuel-matrix interaction on the fuel performance of U-Mo/Al dispersion fuel were investigated. Fuel-matrix interaction bears the causes for breakaway swelling that can lead to a fuel failure under a high-power irradiation condition. Fission gas atoms are released from U-Mo particles to the interaction layer via diffusion and recoil. The fission gases released from the U-Mo and produced in the ILs are further released to the IL-Al interface by diffusion in the IL and recoil. Large pore formation at the IL-Al interface is attributed to the active diffusion of fission gas atoms in the ILs and coalescence between the small bubbles there. A model calculation showed that IL growth increases the probability of forming a breakaway swelling condition. ILs are connected to each other and the Al matrix decreases as ILs grow. When more ILs are interconnected, breakaway swelling can occur when the effective stress from the fission gas pressure in the IL-Al interfacial pore becomes larger than the yield strength of the Al matrix.

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