Rupture of Al matrix in U-Mo/Al dispersion fuel by fission induced creep

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1. Introduction

U-Mo/Al dispersion fuel has been developed to convert HEU fuel utilized in high power and high flux research reactors to LEU fuel. The fueled zone in which U-Mo fuel particles are dispersed in Al matrix is called meat.

After irradiation, some part of the Al matrix showed rupture between neighboring U-Mo fuel particles in some plates with high uranium loadings as shown in Fig. 1. This phenomenon was found specifically in the dispersion fuel plate with Si addition in the Al matrix to suppress interaction layer (IL) formation between U-Mo and Al.

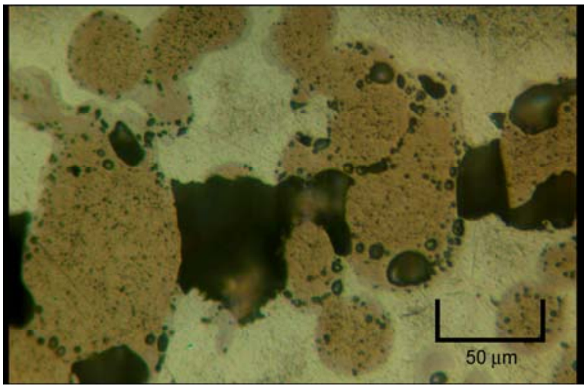


Fig. 1 Optical microscopic image of an irradiated dispersion fuel with Si added Al matrix.

It is known that the stresses induced by fission-induced swelling in U-Mo fuel particles are relieved by creep deformation of the IL, surrounding the fuel particles, that has a much higher creep rate than the Al matrix [1]. Thus, when IL growth is suppressed, the stress is instead exerted on the Al matrix. The observed rupture in the Al matrix is believed to be caused when the stress exceeded the rupture strength of the Al matrix.

In this study, the possibility of creep rupture of the Al matrix between the neighboring U-Mo fuel particles was examined using the ABAQUS finite element analysis (FEA) tool [2].

2. Method

Two representative irradiated plates were selected for the ABAQUS simulation. One is a dispersion fuel with a pure Al matrix that showed high IL growth during irradiation, and the other is a dispersion fuel with an Al matrix with 5 wt% Si addition that showed low IL growth. Irradiation data for the plates are summarized in Table 1.

Table 1 Summary of irradiation data for plates.

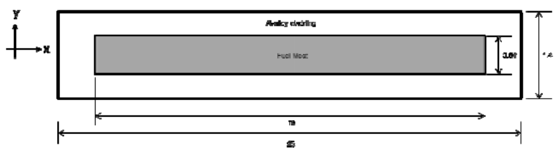
Plate ID	Fuel type	Irradiation time (EFPD)	Fission density at hot side (10^{21} f/cm^3)	Al matrix fracture
A	U-10Mo/Al	257	5.5	No
B	U-7Mo/Al-5Si*	98	5.5	Yes

*Silicon content in weight percent.

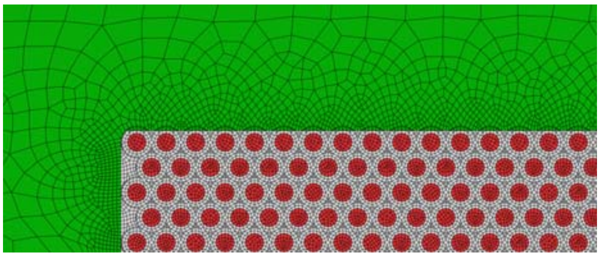
Al creep rupture data are available in [3]. Fuel meat temperature during irradiation is typically below ~150ºC [4]. For both plates A and B, Al creep data obtained at 140ºC were used to predict the rupture time adopting a hypothetical equivalent stress exerted on the Al matrix during irradiation. The predicted rupture time then was compared with the total irradiation time.

A schematic illustration of the cross section of fuel plate is shown in Fig. 2(a). Two dimensional FEA simulation was performed with the consideration of the transversal power distribution of the plate.

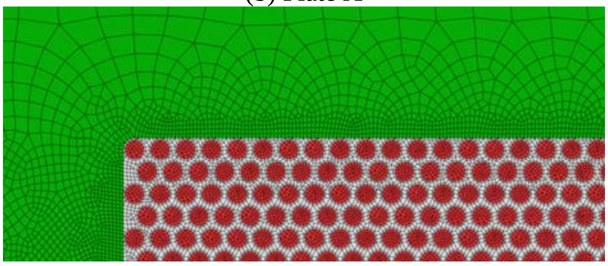
The schematics for the finite element mesh design for the plates are shown in Fig. 2(b) and (c). It is assumed that U-Mo fuel particles are distributed with an FCC array in the meat. The generalized plane strain condition was applied to the mesh.



(a) Cross section of fuel plate



(b) Plate A



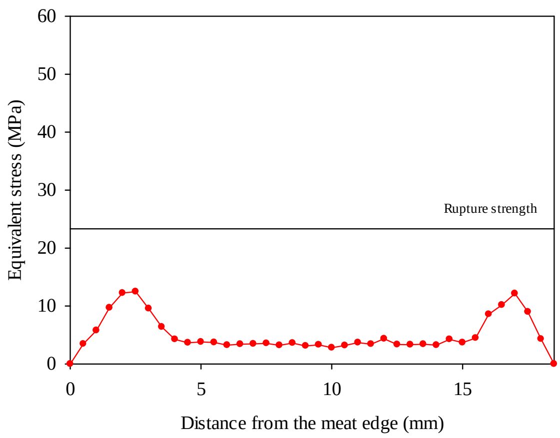
(c) Plate B

Fig. 2 Finite element modeling for each plate.

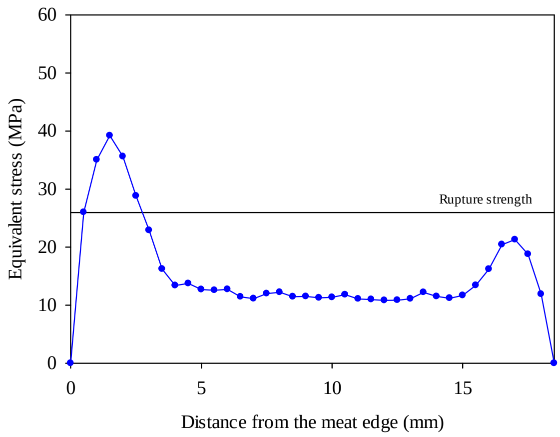
IL growth during irradiation was implemented in the simulation by assigning different field variables to change material properties at the designated analysis time.

3. Results

Fig. 3 shows the equivalent stress distribution in the Al matrix for each plate. The magnitude of the stress becomes largest at 2 – 3 mm away from the meat edge. This peak stress location is consistent with the location where the rupture in the Al matrix was observed. A network of IL became the continuous phase in plate A at 75 EFPD while the Al matrix remained continuous in plate B until the end of life.



(a) Plate A

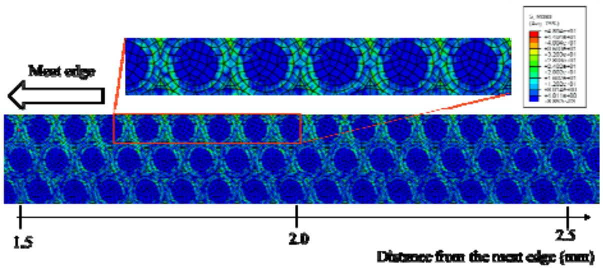


(b) Plate B

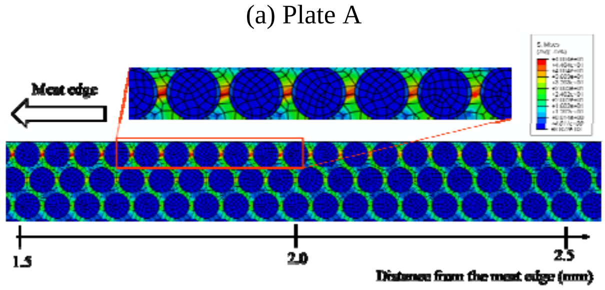
Fig. 3 Equivalent stress for Al matrix in the meat.

Fig. 4 shows a contour of the stress in the meat. It is noticeable that the stress peaks were found repeatedly at the locations between U-Mo fuel particles. The peak stress location in the meat was consistent with that where the Al matrix rupture was found.

The peak magnitude of the equivalent stress for plate A is indeed lower than the creep rupture strength of Al alloy for the whole irradiation, whereas for plate B it exceeds the creep rupture strength. Thus, the creep deformation is considered to be the underlying mechanism for the Al rupture.



(a) Plate A



(b) Plate B

Fig. 4 Contour of equivalent stress for Al matrix. Higher magnitude of stress occurs in the Al matrix between U-Mo fuel particles repeatedly.

Table 2 shows a comparison of the predicted rupture time under given temperature and equivalent stress, and total irradiation time of each plate. Life-averaged equivalent stress at the peak stress location was used to predict the creep rupture time. It is noticeable that the predicted rupture time for plate B is shorter than its irradiation time, so that Al rupture occurs at early irradiation time. However, Al creep rupture is not expected to occur in plate A during whole irradiation period because of the lower stress.

Table 2 Comparison of irradiation time and predicted rupture time Al matrix for each plate.

Plate ID	Peak stress location (mm)*	Life-averaged equivalent stress at the peak stress location (MPa)	Irradiation time (hr)	Predicted rupture time (hr)
A	2.5	12.5	6168	329318
B	2.0	39.2	2352	17.8

*Distance from the meat edge at hot side.

4. Conclusions

The possibility of Al rupture due to creep deformation for two different dispersion fuel plates used for research reactors was examined using ABAQUS FEA simulation. The ABAQUS simulation was consistent with the post-irradiation observation. The predicted rupture time for a plate was much shorter than its irradiation life indicating a rupture during the irradiation. The higher stress leads Al matrix to early creep rupture in this plate for which the Al matrix with lower creep strain rate does not effectively relieve the stress caused by the swelling of the U-Mo fuel particles. For the other plate, no rupture was predicted for the given irradiation condition.

The effect of creeping of the continuous phase on the state of stress is significant. The overall magnitude of equivalent stress decreases when the creep deformation of the continuous phase increases.

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