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Modeling of blistering temperature for KJRR-LTA fuel plates

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1. Introduction

Many efforts have been carried out to qualify the U-7Mo/Al-5Si dispersion fuel used in Kijang research reactor (KJRR). Among these efforts, a full-sized lead test assembly (LTA) with 21 fuel plates, which was fabricated by Korea Atomic Energy Research institute, had been irradiated successfully in Advanced Test Reactor in Idaho National Laboratory during 216.6 effective full power days (EFPD), achieving local maximum burnup of about 84% U^{235} depletion.

Those irradiated fuel plates were examined via post-irradiation examination (PIE), and eleven fuel plates were selected to experience the traditional blister threshold tests to identify the fuel operating temperature limits under normal operations and anticipate transients. During the test, each irradiated plate was exposed at the elevated temperature for a period of time and visually examined, and this process is iterated with higher temperature setting until a blister occurs. The blister temperature is then defined as the temperature where blisters were observed during anneal cycles. Fig. 1 shows the observed blisters of an irradiated plate after the anneal cycle with temperature at 425 °C with 20 minutes.

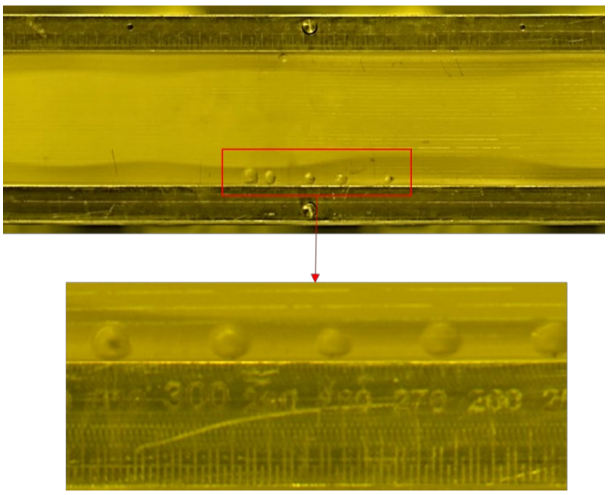

Fig. 1 Image of a surface of irradiated plate from LTA after blister threshold test at 425 °C with 20 minutes.

It is typically known that blisters in metals form due to the gas coalescence at the sites of excess defects including pores, grain boundaries, or microcrack [1].

The gaseous fission products are built up inside of UMo fuel particles, and they are released toward the matrix region by recoil and athermal diffusion during irradiation. It is believed that those released gaseous fission products are entrapped and coalesced into pores at fuel-clad interfaces in the high burnup region, causing the formation of blisters on the surface under the elevated temperature condition.

The formation of blisters on the metal surface typically causes the plastic deformation by expanding gases entrapped [2], indicating that the blister formation follows the plastic deformation of the cladding. The gas pressure inside blisters should be higher than the yield strength of a cladding of aluminum alloy (AA) 6061 to cause plastic deformation of the cladding surface, entailing the formation of large-sized blisters.

In this paper, we estimate the pore pressure inside blisters using fission gas release models and analyze the irradiation- and temperature-dependent yield strength of the cladding. Then, we compare the pore pressure inside blisters and yield strength of cladding at the elevated temperature of blister limit tests. It was found that the yield strength at high temperature and pore pressure are comparable and blister-threshold-temperature limit can be obtained as a function burnup for the irradiated fuel plates from LTA.

2. Methods

2.1 Pore pressure inside blisters

Pore pressure inside blisters (P) is calculated using ideal gas law as follows:

$$P = n_{fg}RT/V \quad (1)$$

where n_{fg} is the number of fission gases inside pore, R is gas constant, T is temperature, and V is the volume of pore. The volume of pore is given using the measured porosity during PIE.

The number of fission gases (n_{fg}) in the pore at blistered region of the clad surface can be obtained by multiplying the total amount of produced fission gases to the total release fraction. Two mechanisms are involved for fission gases to migrate from UMo fuel particle inside to the region where blisters form; athermal diffusion and fission-induced recoil. Athermal diffusion of fission gases occurs during irradiation period in the operating temperature regime below 200 °C. Fission-induced recoil is also a major migration mechanism since the size of fuel particles is comparable to the fission-recoil range (~6.8 μm) [3].

The total release fraction is calculated using Eq. (2) as follows:

$$F_t = F_c + F_d \quad (2)$$

where F_c and F_d is the release fraction by recoil and diffusion, respectively. Each release fraction is given by Eq. (3) and (4):

$$F_d = \frac{4}{r}\sqrt{\frac{Dt}{\pi}} - \frac{3Dt}{2r^2} \quad (3)$$

$$F_c = \frac{3}{4}\frac{\mu}{r} - \frac{1}{16}\left(\frac{\mu}{r}\right)^3 \quad (4)$$

where D is the diffusion coefficient, r is the radius of fuel particle, t is irradiation time, and μ is the recoil range.

Thermally-activated diffusion also possibly occurs during annealing condition of blister-threshold test at temperature higher than 400 °C. However, a coefficient for thermal diffusion of Xenon in metallic U alloys is four orders of magnitude lower than that for athermal diffusion, and it was reported by Castleman et al. that Xenon was not found to diffuse through aluminum in the temperature range of 295 to 473 °C [4]. Also, its effect is minimal since the time period of each anneal cycle is much shorter than irradiation period. In this regard, thermal diffusion of fission gases is not considered to calculate the pore pressure.

2.2 Yield strength of irradiated cladding

The yield strength of the irradiated cladding in the elevated temperature up to 450 °C was obtained based on the available data in literature [5,6,7]. Fig. **2** shows the available data of yield strength for AA 6061. The widely-accepted data of yield strength for aluminum alloys in temperature higher than 94 °C are available in ASM Metals handbook [5], Aluminum Design Manual (ADM) [6] or European Code 9 (EN 1999-1-2) [7], but properties in those literature are significantly conservative when temperature is higher than 250 °C. Those properties also do not contain any effects of heat treatment or cold-working from fabrication process of a fuel plate.

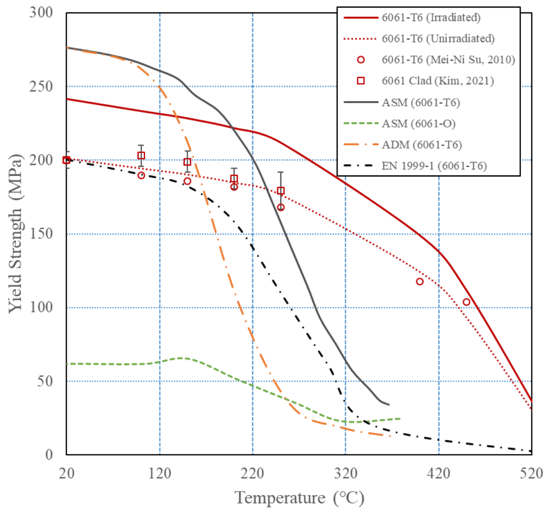

Fig. 2 Temperature-dependent yield strength of the irradiated cladding.

The measured data of yield strength for the cladding by Kim et al.[8] up to 250 °C can be regarded as a representative yield strength of as-fabricated cladding but the data up to 450 °C is not available. Thus additional dataset of yield strength for tempered AA 6061-T6 measured up to 550 °C by Mei-Ni Su et al.[9] was used to predict the yield strength at the temperature higher than 250 °C.

The effect of irradiation hardening is also considered such that the yield strength of irradiated AA6061 up to a fluence of 8.88×10^{21} n/cm^2 (E>0.1 MeV) is expected to increase by 20%, based on available data by Farrell et al [10]. The yield strength of the irradiated cladding as a function of temperature is used to determine the pore pressure equals the yield strength at a given temperature.

2.3 Blister-threshold temperature limit

Blister-threshold temperature limit is a temperature limit, implying that blisters could occur whenever temperature exceeds the limit for a given fuel burnup. This envelope is typically obtained by an empirical fitting as a function of fission density. However, as shown in Fig. 3, it is possible to obtain the temperature limit where the calculated pore pressure (P) at a given burnup starts to exceed the yield strength of the cladding as a function of temperature. The blister-threshold temperature limit was obtained collecting all intersection points of two curves for pore pressure and yield strength as a function of temperature.

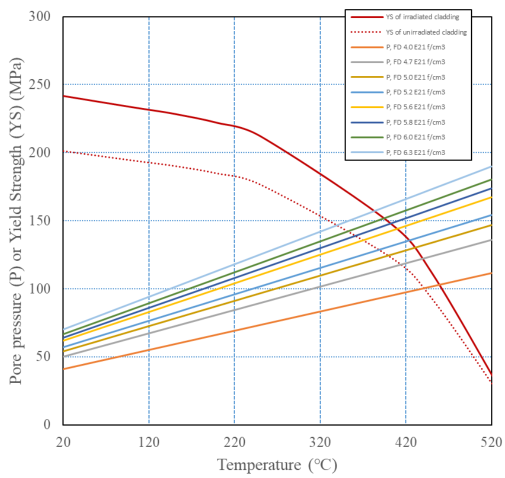

Fig. 3 Comparison among pore pressures with different burnup and temperature-dependent yield strength of cladding.

3. Results and discussion

Fig. **4** shows the blister-threshold temperature limit obtained by collecting all intersection points between multiple curves for pore pressures with a given fission density and curves for yield strength of the unirradiated (i.e., red-dotted line) or irradiated cladding (i.e., red-solid line) in Fig. **3**. In Fig. **4**, two regions are presented: Region I for the temperature range where pore pressure is in-between yield strength of unirradiated and irradiated cladding, and Region II for temperature range where pore pressure exceed the yield strength of irradiated cladding. The limit bounding for Region I (black-dotted line) can be used to predict the strong conservative temperature limit, while that for Region II (red-solid line) can be used for best-estimated temperature limit.

The comparison between test data with different blister temperature showed that the predicted threshold temperature limit combined with the yield strength of irradiated cladding estimate agreeable the blister temperature as a function of fission density.

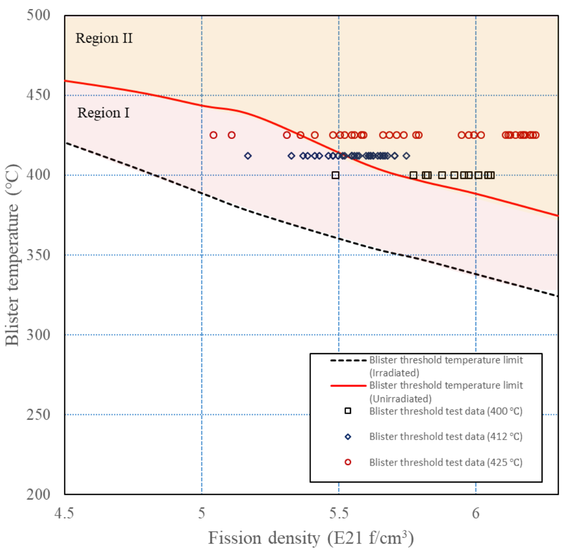

Fig. 4 Comparison between blister threshold temperature limits and test data from KJRR plates.

4. Conclusions

The blister-threshold temperature limit for irradiated plates from KJRR-LTA is predicted based on analytic approaches using fission gas release model with pore pressure prediction and irradiated yield strength of the cladding. The pore pressure inside blisters is calculated when the number of fission gases inside pore, and it is compared to the yield strength of the cladding. It was found that the blisters at a given temperature and fuel burnup possibly form whenever pore pressure exceeds the yield strength of the cladding. The blister-threshold temperature limit was also obtained as a function of fuel burnup based on the proposed approaches, which is agreeable to experimental data. It was shown that the threshold temperature limits can be obtained for best-estimation as well as conservative estimation depending on whether the effect of irradiation on yield strength of the cladding is involved or not. Those approaches could be verified and validated with blister threshold test data from other irradiation campaign in the future.

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