Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2017

Numerical Study of Crack Behavior in UO_2-5 vol% Mo Micro-cell

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1. Introduction

Metallic micro-cell nuclear fuel pellet with metal network for improving thermal conductivity has been studied as one of the promising accident-tolerant fuels (ATFs) [1]. The continuous formation of Mo network in the UO_2-5 vol% Mo micro-cell pellets effectively increases their thermal conductivities, which can decrease the temperature gradient across the pellets, thereby reducing the maximum tensile hoop stress in the pellets. Our previous numerical studies estimated that UO_2-5 vol% Mo micro-cell pellets could not only reduce 26% of the central temperature of pellet, but also decrease the maximum hoop stress of pellet 52% than UO_2 pellet [2-4]. However, based on the previous results, the tensile hoop stresses in the outermost regions of the pellets are larger than the fracture strength of UO_2, implying that crack propagation occurs in those regions. Therefore, it is necessary to investigate the effect of Mo network in the UO_2-5 vol% Mo micro-cell pellets on the crack propagation. Here we numerically studied the crack behavior of UO_2-5 vol% Mo micro-cell.

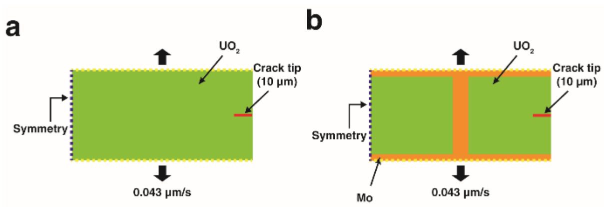

Figure 1. (a) Boundary conditions of UO_2 model. (b) Boundary conditions of UO_2-5 vol% Mo micro-cell model.

2. Simulation model

To investigate the effects of Mo network in the micro-cell on the crack propagation, we set up the simplified model as shown in Figure 1. The micro-cell was simplified as the unit-cell model [5], and the Mo network was distributed with uniform thickness. Specifically, the unit cell had a height of 400 μm, a width of 200 μm, and the initial crack tip size of 10 μm. The stress in micro-cell was calculated by solving the elastic/plastic stress-strain equation (Eq (1), (2), (3), and (4)) as follows:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + F_x = \rho \frac{\partial^2 u_x}{\partial t^2} \quad (1)$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + F_y = \rho \frac{\partial^2 u_y}{\partial t^2} \quad (2)$$

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} + F_z = \rho \frac{\partial^2 u_z}{\partial t^2} \quad (3)$$

$$\sigma = E\varepsilon^e = E(\varepsilon - \varepsilon^p) \quad (4).$$

The fracture formation in micro-cell was calculated by solving equation (Eq (5), (6), (7), and (8)) as follows:

$$G_c = \int_0^w \sigma\, dw \quad (5)$$

$$\sigma = K_n u_n \quad (u_n < \delta) \quad (6)$$

$$\sigma = \left(\frac{\delta - u_n}{\delta_c - u_n}\right) (\delta \le u_n \le \delta_c) \quad (7)$$

$$\sigma = 0 \quad (u_n > \delta_c) \quad (8).$$

The equations (6), (7), and (8) are governing equations of cohesive zone model in fracture mechanics [6, 7]. The material properties of UO_2 and sintered Mo were adopted from the references [7-10] for the calculation of fracture behavior of micro-cell. The mechanical boundary conditions in this study were as follows: (1) symmetry condition to the left side, (2) free condition to the right side, and (3) strain rate condition (chapter 3.1) and symmetry condition (chapter 3.2) for the top and bottom sides. The main assumptions for the numerical study were (1) Mo wall thickness was uniform, (2) the interface between UO_2 and Mo was perfect, and (3) the irradiation effect of micro-cell was ignored. This study was carried out using Abaqus/CAE 2016 software.

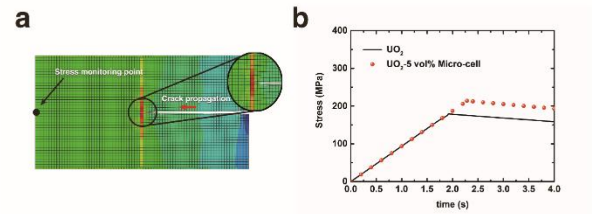

Figure 2. (a) Numerical result of crack propagation in UO_2-5 vol% Mo micro-cell. (b) Comparison of crack propagation behavior between UO_2 and UO_2-5 vol% Mo micro-cell.

3. Result and discussion

3.1 Comparison of crack behavior under the application of constant strain rate

We monitored the crack propagation of UO_2 and UO_2-5 vol% Mo micro-cell models under the same strain rate as 0.043 μm/s for pure mechanical effects of Mo networks on crack behaviors (Figure 2). It should be noted that in this comparison, we did not input the residual stresses to investigate the mechanical effects of Mo walls only on the crack propagation, because Mo has higher toughness and tensile strength than UO_2. The mechanism of crack propagation is as follows: the stress concentration occurs around the crack tip, and the stress gradually increases. Once it reaches the maximum level of the material or the composite, the stress decreases while crack is propagated. UO_2-5 vol% Mo micro-cell delayed the fracture time in the monitoring location in Figure 2 by 20%, compared to UO_2, meaning that the insertion of Mo in the micro-cell increased effective toughness and tensile strength to retard crack propagation.

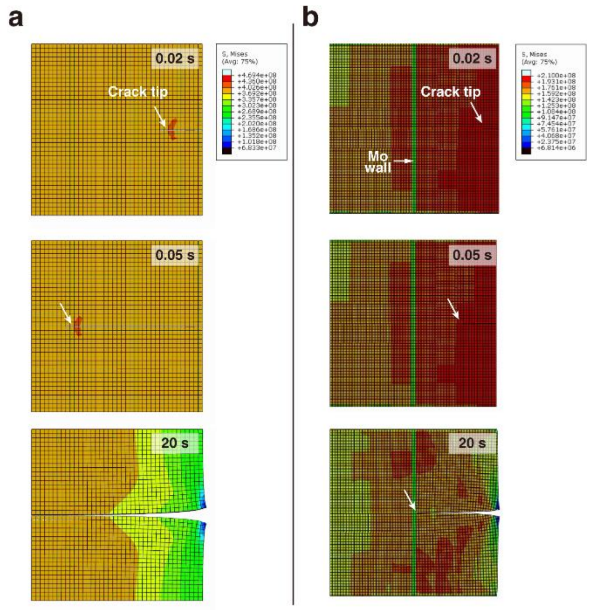

Figure 3. Comparison of the crack behaviors of (a) UO_2 and (b) UO_2-5 vol% Mo micro-cell.

3.2 Comparison of crack behavior under the application of thermally-induced residual stress

Under linear heat generation rate (LHGR) of 200 W/cm, the tensile hoop stresses in steady-state thermal stress simulation were over 400 and 190 MPa in the outer region of the UO_2 and UO_2-5 vol% Mo micro-cell pellets, respectively [4]. We input these thermal stresses to the fracture models as residual stresses. As a result, while the crack in UO_2 was fully propagated at 0.06 second, UO_2-5 vol% Mo micro-cell took twice more time until the crack reached the Mo wall region in the middle of the numerical domain (Figure 3). More importantly, the Mo wall structure was well maintained for our simulation time of 20 sec, implying that the Mo wall could act as an effective barrier to crack propagation.

4. Conclusions

The crack behavior of UO_2-5 vol% Mo micro-cell was numerically investigated. If the interface between UO_2 and Mo was perfect, the Mo wall in UO_2-5 vol% micro-cell could effectively retard the crack propagation in the pellet. The formation of Mo network in the UO_2 pellets cannot contribute only to the decrease of temperature gradient across the pellet, thereby relieving the associated thermal stresses, but also to the improvement of the structural integrity under crack propagation.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (NRF-2016M2A8A5902940).

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