Numerical Investigation of Thermal Stress in UO_2-Mo Micro-Cell Fuel Pellets

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1. Introduction

Many studies of accident-tolerant fuels (ATFs) have been actively carried out to enhance safety of fuel for LWR (Light Water Reactor) [1]. One strategy of those is to fabricate the composite of UO_2 and high thermal conductive material, thereby lowering thermal budget of nuclear fuels [2,3]. The recently fabricated UO_2-Mo micro-cell pellets showed high thermal conductivities with minimal inclusion of Mo content, demonstrating the promise of ATFs [4]. In this study, we numerically investigated the thermal and mechanical characteristics of UO_2-5 vol% Mo micro-cell pellets. Compared to the conventional UO_2 pellets, the micro-cell pellets not only lowered the maximum temperature of the pellet by 26%, but also decreased the maximum thermal hoop stress of the pellet by 52%.

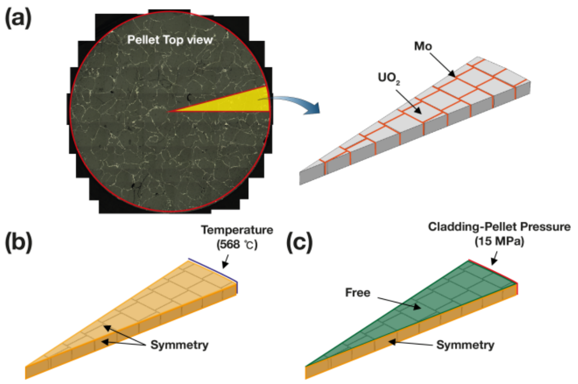

Figure 1. (a) Optical image (left) and 3D simulation model (right) of UO_2-5 vol% Mo micro-cell pellet. (b) Thermal boundary conditions of 3D simulation model. (c) Mechanical boundary conditions of 3D simulation model.

2. Simulation model

We set up the 3D simulation model by slicing the UO_2-5 vol% Mo micro-cell pellets from the top view as shown in Figure 1(a). The 3D simulation model had a radius of 4 mm, a height of 0.2 mm, and a unit micro-cell size of 400 μm. The thermal and mechanical properties of UO_2 and Mo were adopted from MATPRO and CRC Handbook [5, 6]. It should be noted that we adopted Young's modulus of Mo from the sintered Mo data [7]. The thermal boundary conditions of the 3D simulation model (Figure 1b) were as follows: (1) symmetric conditions to the top, the bottom, and the sides of the model, (2) constant temperature of 568 ℃ to the outer side of the model, and (3) uniform heat generation, following a linear heat generation rate of 200 W/cm, of the model. The mechanical boundary conditions of the 3D simulation model (Figure 1c) were as follows: (1) free condition to the top and the bottom of the model, (2) symmetric condition to the sides of the model, and (3) constant pressure of 15 MPa, mimicking pellet-cladding pressure, to the outer side of the model. We solved conventional heat equation and elastic/plastic stress-strain equation to calculate temperature and hoop stress distributions of the model. The main assumptions for the simulation were (1) the micro-cell had uniform wall thickness of Mo, and (2) the interface between UO_2 and Mo was perfect.

3. Result and discussion

3.1 Comparison of pellet temperature distribution

We first compared the temperature distribution between UO_2 and UO_2-5 vol% Mo pellets (Figure 2). The temperature gradient of the UO_2-5 vol% Mo pellet significantly decreased, compared to the UO_2 pellet. It was attributed to the fact that the continuously connected metallic walls of Mo effectively increased thermal conductivities of the UO_2-Mo micro-cell pellet. Consequently, the inclusion of 5 vol% Mo to UO_2 lowered the maximum temperature at the core of UO_2 pellet by 26%.

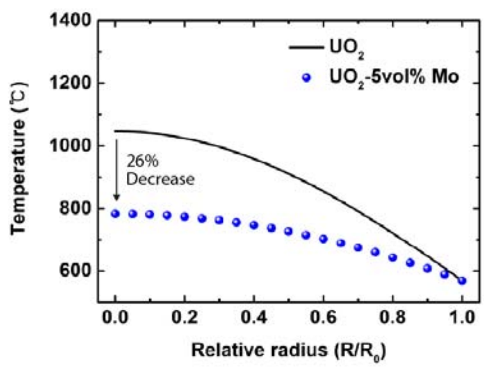

Figure 2. Comparison of temperature distributions between UO_2 and UO_2-5 vol% Mo micro cell pellets.

3.2 Comparison of thermal hoop stress

We further investigated the thermal hoop stress of UO_2-5 vol% Mo pellet as shown in Figure 3. The maximum thermal hoop stress was reduced by 52 % in UO_2-5 vol% Mo pellet, compared to that of UO_2 pellet, and the overall hoop stress gradient significantly decreased in UO_2-5 vol% Mo pellet. The decrease in the maximum thermal hoop stress of the micro-cell pellet was mainly attributed to the decreased temperature gradient of the micro-cell pellet. Importantly, for the UO_2-Mo network in the inner part of the pellet, the tensile stresses were applied to the Mo walls, while the compressive stresses were acted in UO_2, due to larger thermal expansion coefficient of UO_2 than Mo. The maximum stress of Mo wall was about 5% above the yield stress of Mo, which did not reach the tensile and fracture stresses of Mo.

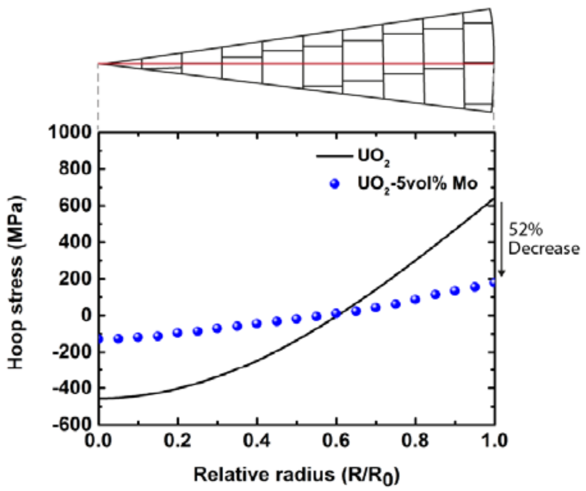

Figure 3. Hoop stress distributions of UO_2 and UO_2-5 vol% Mo micro cell pellet.

4. Conclusion

The thermal and mechanical effects of Mo distribution in the UO_2-Mo micro-cell pellet were numerically investigated. The calculations were mainly based on the assumption of perfect interface between UO_2 and Mo. The inclusion of well-connected 5 vol% Mo to UO_2 pellets not only decreased the maximum temperature of the fuel pellet by 26%, but also lowered the maximum thermal hoop stress of the pellet by 52%, which showed the potential of the significant improvement in the safety of nuclear fuel.

ACKNOWLEDGEMENT

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