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Development Status of Metallic and Ceramic Microcell UO_2 Pellet for ATF

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1. Introduction

Accident Tolerant Fuel (ATF) concepts are being suggested and evaluated to mitigate the consequences of an accident [1-4]. At KAERI, a microcell UO_2 pellet as an ATF pellet is being developed to enhance the accident tolerance of nuclear fuels under accident conditions as well as the fuel performance under normal operation conditions [5-7].

The microcell consists of UO_2 grains or granules enveloped by thin cell walls, which are continuously connected. Fig. 1 shows a conceptual schematic of a microcell UO_2 pellet. The main purpose of the microcell UO_2 pellets is to minimize the release of highly radioactive and corrosive fission products from the fuel, and to reduce the pellet temperature for enhanced fuel safety margin. There are two kinds of microcell UO_2 pellets, classified according to the material type composing the cell wall. These are metallic and ceramic micro-cell UO_2 pellets with distinct features.

The metallic microcell UO_2 pellet is a highly thermal conductive pellet having a continuously connected metallic wall. A cold pellet would reduce the fission product release by slowing down the diffusion. The reduced temperature gradient mitigates the PCMI (Pellet-Cladding Mechanical Interaction) failures during a transient operation. In addition, a micro-cell UO_2 pellet with high thermal conductivity will significantly increase the safety margin under design basis accidents such as a LOCA (Loss-Of-Coolant Accident) as well as the thermal and operational margin under normal operation conditions.

The ceramic wall in ceramic microcell UO_2 pellets is composed of an oxide phase with chemical affinity to volatile fission products (Cs and I), and acts as multiple traps to immobilize the volatile fission products. That is, the ceramic microcell walls can block the migration of fission products to the pellet outside. The increased retention capability of the fission products will reduce the stress corrosion cracking at the inner surface of the cladding as well as the rod internal pressure. In addition, a soft ceramic-wall facilitates the fast creep deformation of the pellets, thereby reducing the mechanical stress of the cladding under operational transients. These benefits are expected to enhance the robustness of a fuel rod during a severe accident as well as during normal operation. The large-sized grain and mesh-like rigid wall structures are also expected to prevent the massive fragmentation of pellets during a severe accident thereby reducing the release of retained radio-toxic fission products into the environment.

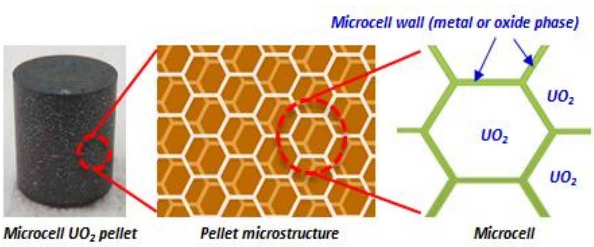

Fig. 1. Conceptual schematic of microcell UO_2 pellet

At KAERI, the microcell UO_2 fuel pellet concepts were designed, and the fabrication process of those fuel pellets embodying the designed concept was developed. Assessments of the out-of-pile properties and in-reactor performances of microcell UO_2 pellet are being carried out. In this presentation, we intended to describe the development status of the microcell UO_2 pellet for ATF.

2. Development of Microcell UO_2 Pellet

Many candidate metals for a metallic microcell wall material have been assessed and screened, based on their physical properties such as the thermal conductivity, neutron absorption cross section, melting temperature and so on. Mo and Cr were primarily selected as the metallic cell wall materials because they have relatively high melting temperature, high thermal conductivity, and manageable neutron absorption cross section. Above all things, it is significantly required that the Mo and Cr are compatible with a UO_2 matrix under the sintering conditions of the pellet fabrication process.

Fig. 2(a) shows the microstructure of a 5 vol% Cr metal phase containing metallic microcell UO_2 pellets, in which the microcell concept is successfully implemented. These pellets were fabricated by the co-sintering of metal powder over-coated UO_2 granules through a conventional sintering process. Metal powder over-coated UO_2 granules, which were prepared by mixing metal powders and UO_2 granules, were pressed into green pellets. After that, those green pellets were sintered under a dry hydrogen atmosphere. The sintered pellet density and averaged cell (granule) size of fabricated 5 vol% Cr metallic microcell UO_2 pellet were 10.5 g/cm^3 and ~290 μm, respectively.

The ceramic microcell wall materials require chemical affinity to Cs to form stable compounds with incorporated Cs. Because the fission yield of Cs is roughly ten-times larger than that of iodine, the chemical affinity of the wall to cesium may deeply impact the retention capability of the fission products. Insolubility of the wall materials in a UO_2 matrix is also an important requirement to maintain the microcell structure. The recent test results for Al-Si-O doped UO_2 suggests the chemical trapping of volatile fission products in an SiO_2-based additive phase, and decreased possibility of the availability of aggressive species in the inside cladding. We therefore selected several SiO_2-based mixed oxides as additive candidates for ceramic cell wall materials.

To fabricate the ceramic microcell UO_2 pellets, a conventional liquid phase sintering technique has been applied. A powder mixture of UO_2 and additives was pressed into green pellets, which were then sintered at an elevated temperature at which the additives for the wall materials formed a liquid phase, penetrating through grain boundaries and enveloped UO_2 grains to make the designed ceramic microcell.

Fig. 2(b) shows the microstructure of the ceramic microcell UO_2 pellet. This pellet was obtained by mixing a 0.6 wt% SiO_2-TiO_2 oxides mixture with UO_2 powder and then sintering the powder mixture at 1720 ℃ for 4h in a dry hydrogen atmosphere. The sintered pellet density and averaged cell (grain) size were 10.76 g/cm^3 and ~80 µm, respectively.

In the development of nuclear fuel, the irradiation behavior of the developed fuel material must be considered based on various aspects (pellet microstructure, pellet structural integrity, cell wall soundness, cell wall material behavior and redistribution, reaction between cell wall material and fission product, etc.).

Through cooperation with Thor Energy, Norway, a Halden irradiation test of the microcell UO_2 pellets is now in progress. KAERI is participating in the International Thorium Consortium organized by Thor Energy. Two kinds (ceramic and metallic) of microcell UO_2 pellets were fabricated in accordance with the requirements for the Halden irradiation test. The number of samples was sufficiently provided for manufacturing the instrumented rigs. The irradiation test rigs with instrumentations were manufactured at the Institute for Energiteknikk (IFE), Norway.

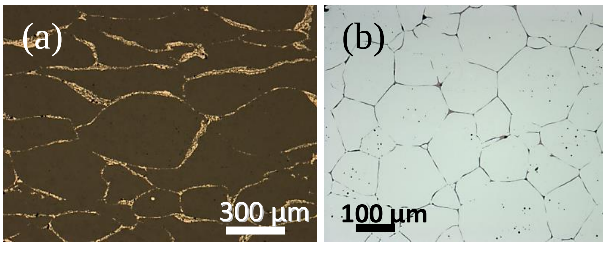

Fig. 2. Microstructure of the microcell UO_2 pellets;
(a) Cr metallic microcell, (b) Si-Ti-O ceramic microcell.

Until now, the temperature difference between the UO_2 reference pellet and Cr metallic microcell UO_2 pellet is being consistently maintained. The irradiation test of microcell UO_2 pellets is ongoing at above ~12,000 MWd/mtU according to the plan, and is proceeding to reach a higher burnup.

4. Summary

As an ATF pellet, the microcell UO_2 pellets are being developed to enhance the accident tolerance of nuclear fuel. The material concepts of ceramic and metallic microcell UO_2 pellets are designed, and the fabrication process of microcell UO_2 pellets embodying the designed concept has been developed.

Observation of the in-reactor performance and behavior of the developed pellets is progressing through Halden irradiation testing. According to the expectations, the excellent performances of the microcell UO_2 pellets are being verified by the online measurement data of Halden irradiation tests.

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