Manufacturing Optimization of Mo-microcell UO_2 Fuel for Commercial-scale Fabrication

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1. Introduction

Since the Fukushima Daiichi accident, accident-tolerant fuel (ATF) has been developed worldwide to enhance the safety margins of light water reactors (LWRs) under design-basis and beyond-design-basis conditions. The effort has been directed at reducing fission gas release and the stored energy of the pellet through large-grain doped UO_2, uranium-dense fuels of high thermal conductivity such as U_3Si_2, and composite pellets containing a high-conductivity second phase. Microcell fuel belongs to the last group, but differs in that the second phase is not randomly dispersed: it forms continuous cell walls that enclose the UO_2 cells.

KAERI has developed a microcell-structured advanced fuel with improved safety and operating performance (MISO), in which a continuous three-dimensional metallic molybdenum (Mo) network is formed within the UO_2 matrix [1–3]. Because the thermal conductivity of Mo far exceeds that of UO_2 at operating temperatures, the Mo network serves as an efficient heat conduction path. The thermal conductivity of the Mo-microcell pellet exceeds that of a conventional UO_2 pellet over the whole temperature range of interest, reaching about twice that of UO_2 at high temperature, as shown in Fig. 1 [4]. The lower fuel centerline temperature and flatter radial temperature distribution suppress fission gas release and reduce the thermally induced expansion and swelling of the pellet, which in turn mitigates pellet-cladding mechanical interaction.

Previous studies verified the feasibility and thermal performance of the Mo-microcell fuel at the laboratory scale, where batch-type furnaces and high-purity raw materials were employed. For commercialization, however, the pellets must be produced with commercial-grade UO_2 powders on existing production lines equipped with automatic presses and continuous open-sintering furnaces. Under such high-throughput conditions, powder flowability, density control, the reuse of scrap, and commercial additives such as lubricants and pore formers can all influence the compaction and densification behavior of the UO_2-Mo system. In this study, commercial process parameters were examined and optimized for the fabrication of Mo-microcell pellets, and the robustness of the Mo network was evaluated.

2. Experimental

2.1 Direct conversion UO_2 powder

Commercial-scale Mo-microcell pellets were prepared with direct conversion (DC) UO_2 powder rather than the ammonium diuranate (ADU)-derived powder used in earlier studies. In consideration of the characteristics of the DC powder, the compaction pressure was set lower than that used for the ADU-based process, and Mo blending, compaction, and sintering were then carried out.

2.2 Lubricant and pore former

To determine the appropriate lubricant content, pellets were prepared with Acrawax additions of 0–0.05 wt%, and the lubricant blending time with the MISO powder was varied at four levels (5, 10, 30, and 60 minutes). Ammonium zirconium basic carbonate (AZB) was introduced as a pore former during the sieve mixing step.

2.3 Quantification of Mo network continuity

The continuity of the Mo network was quantified by the affected metallic surface (AMS), defined as the fraction of the cell-boundary length over which the Mo wall is discontinuous relative to the total boundary length of a fully continuous network [5]. In this study, the AMS was measured from optical microscopy (OM) images of pellet cross sections. A central region of interest was selected to exclude vignetting near the image edges, the UO_2 cells were segmented by a distance-transform watershed algorithm, and each cell-boundary segment was classified as Mo-covered or open to obtain the AMS.

3. Results and Discussion

The DC powder consisted of nearly spherical particles and showed a wider particle size distribution than the ADU powder. This broad distribution raises the possibility of segregation during Mo blending, but the average sintered density decreased by only 0.5% of the theoretical density (TD) relative to pellets fabricated with the conventional ADU powder. This decrease is within the tolerance of commercial specifications. Locally low-density regions were occasionally found,

but no loss of pellet integrity or of Mo network connectivity was evident in the observed microstructures.

In commercial UO_2 pellet production, an internal lubricant such as Acrawax is admixed to lower die-wall friction and homogenize the green density, whereas die-wall lubrication was used in previous MISO fabrication. Without an internal lubricant, die-wall friction was so severe that the target compaction pressure of 400 MPa could not be reached. The attainable pressure was limited to about 300 MPa, and considerable resistance occurred during ejection of the green pellets. When 0.01 wt% or more of Acrawax was added, the friction decreased markedly, and the pellets were compacted and ejected smoothly at the target pressure. On the other hand, a higher addition of 0.05 wt% lowered the sintered density by about 3% TD relative to the 0.01 wt% case. The decrease is larger than the volume of the added lubricant alone can account for, and the responsible mechanism, which may involve residual carbon or disturbance of the Mo dispersion, remains to be identified. Accordingly, 0.01 wt% was selected as the optimum Acrawax content for the powder-mixed lubrication process. A linear correlation was observed between the AZB content and the sintered density over the range examined, the density decreasing as the AZB addition increased. The AZB content therefore serves as a control variable for tailoring the porosity and density of the pellet to a given manufacturing specification.

The AMS remained within about 8–12% and showed no significant dependence on the blending time within the measurement uncertainty. The radial AMS (AMS_{radial}), evaluated over the boundary segments that obstruct radial heat flow, was determined separately because it is this component that governs the effective thermal conductivity of the pellet. AMS_{radial} remained within 6–9% at all four blending times, indicating that Mo network formation is robust over the whole blending-time range of 5 to 60 minutes, as shown in Fig. 2.

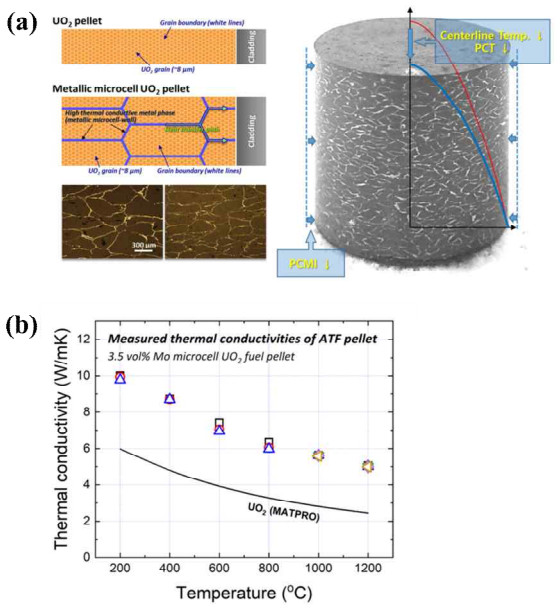


Fig. 1. (a) Concept and microstructure of the Mo-microcell UO_2 pellet [3] and (b) the measured thermal conductivity of a 3.5 vol% Mo-microcell pellet [4].

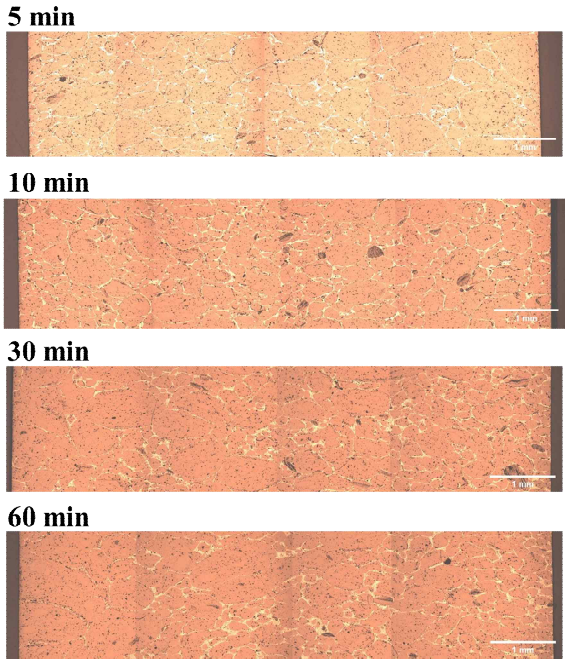


Fig. 2. Cross-sectional microstructures of MISO pellets prepared with different lubricant blending times.

4. Conclusions

Commercial process parameters were applied and optimized for the fabrication of Mo-microcell UO_2 pellets. Commercial UO_2 granules were compatible with the microcell process, and the resulting pellets showed a density decrease of only 0.5% TD relative to the ADU-based pellets. An internal lubricant content of 0.01 wt% Acrawax was identified as the optimum condition for stable compaction, the AZB pore former enabled linear control of the sintered density, and the Mo network continuity was insensitive to the blending time, with the AMS remaining within 8–12% and AMS_{radial} within 6–9% over blending times of 5 to 60 minutes. These findings indicate that the microcell structure responsible for the enhanced thermal performance can be retained when commercial fabrication parameters are applied, supporting the commercialization of the Mo-microcell fuel as a high-performance ATF.

MISO pellets will subsequently be fabricated on existing production lines equipped with automatic press machines and continuous open-sintering furnaces. The thermal diffusivity of the pellets sintered in the commercial furnace will be measured to assess quantitatively whether the conductivity enhancement observed at the laboratory scale is reproduced in the commercially fabricated pellets. The optimized parameters will then be applied to a full production lot, followed by out-of-pile property evaluation.

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