Development of a Perforated Multilayer Pellet Approaching the Theoretical Upper Bound of Composite Thermal Conductivity

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1. Introduction

UO_2 pellets with enhanced thermal conductivity, including high conductivity metals such as Mo, have been developed to lower the fuel centerline temperature and enlarge safety margins. The metallic microcell pellet, in which UO_2 granules are enveloped by continuously connected metal walls, is a representative achievement of this route [1,2]. Composite conduction theory, however, sets a limitation on this approach: the effective conductivity of any isotropic metal–oxide microstructure cannot exceed the Hashin–Shtrikman (HS) upper bound [3], and the measured microcell performance already approaches this limit. The higher parallel (Wiener) bound is accessible only to continuous metal layers aligned with the heat flow. Because heat flow in a cylindrical pellet is intrinsically radial, thin metal layers stacked normal to the pellet axis can exploit this alignment at no thermal cost to the application (Fig. 2).

Layered implementations have been developed before: discrete stacking of UO_2 wafers and Mo discs at Idaho National Laboratory, with the thermal benefit confirmed in TREAT transient irradiation [4-6]. Other concepts are such as a bonded unitary fuel segments with deposited conductive layers [7], and co-pressed sandwich-type pellets [8]. The discrete-stack route, however, multiplies the number of loaded components and relies on mechanical contact interfaces, while a co-sintered multilayer has remained impractical for two reasons.

First, a dense metal layer undergoes less sintering shrinkage while the surrounding oxide compact shrinks substantially, so lamellar cracks develop along the layers. Second, Mo is known to form no metallurgical bond with UO_2 under sintering conditions, so each layer face remains an unbonded plane that destroys the structural continuity of the pellet.

This paper proposes a perforated multilayer concept that resolves both failures with a single design element, summarizes the design analyses performed to establish it, and outlines the verification using surrogate material.

2. Methods and Results

2.1 Perforated Multilayer Concept

Through-thickness openings are formed in each metal layers. During pressing, oxide powder fills the openings; during sintering, the oxide above and below each layer bonds directly to itself through the openings, forming oxide–oxide sintered bridges (Fig. 1). The bridges mechanically anchor the stack and bypass the inert metal–oxide interface, so interlayer cohesion no longer depends on a bond that the material pair cannot provide. The perforation is therefore not a compromise of the conduction path but the enabling feature of the architecture.

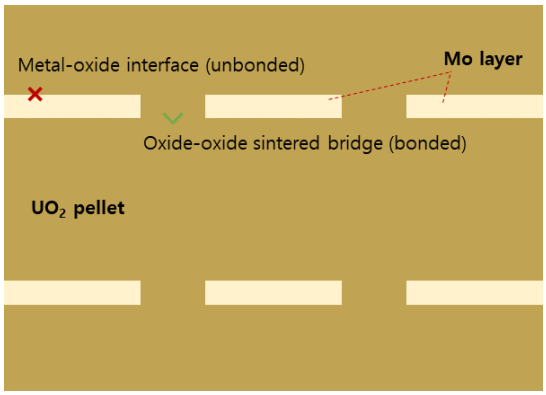


Fig. 1. Sintered-bridge concept: Oxide-oxide bridges (V) anchors the layers while the metal-oxide faces remain unbonded (X).

The reference architecture is a cylindrical pellet containing several equally spaced layers normal to the pellet axis with a metal loading of only a few (~3 vol.%) metallic volume. Candidate perforation patterns include circular hole arrays, straight slots, radially oriented sectors, and mesh-type patterns. The perforation fraction, number of layers, and layer thickness are tied by the fixed metal loading, so the design optimization was conducted considering these parameters parallelly, as described in below section.

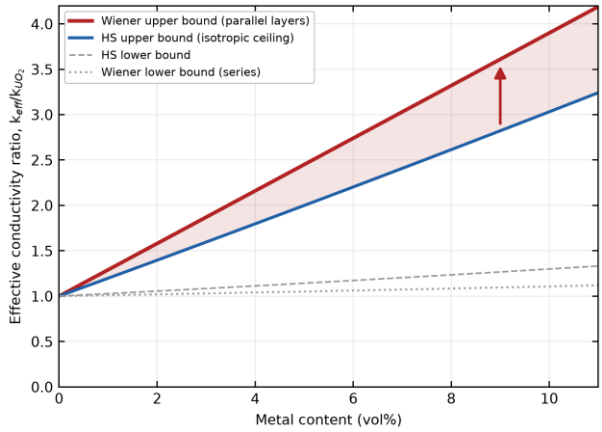


Fig. 2. Bounds of composite conduction: isotropic microstructures are limited by the HS upper bound, while the parallel Wiener upper bound is accessible by aligned continuous layers.

2.2 Thermal Design Analysis

Steady conduction with temperature-dependent properties is solved by a finite-volume method in r-z axisymmetric geometry over a half-period unit cell of the stack, with heat generated in the oxide phase only. Radial sector openings admit an exact angle-averaged treatment because the metal and oxide strips lie parallel to both the radial and axial flux; this treatment was additionally verified against a full three-dimensional solution of the actual sector geometry, and the solver against the analytic solution of a homogeneous cylinder.

2.2.1 Perforation shape optimization

Optimization on perforation shape was conducted. Circular holes isolate heat-generating oxide islands inside the metal and retain a temperature penalty of ~10 K. While radially oriented perforations, arranging parallel to the dominant heat flux, present continuous metal flanks along the entire heat path and make the negligible temperature penalty.

2.2.2 Number of metallic layer and perforation fraction optimization

At fixed metal loading, preliminary calculation on a stack of five layers per pellet, already closely reached to the temperature-reduction potential of the homogenized parallel limit. Further increment of perforation number returns diminishing effect.

The sintering bridge area decreases with increasing perforation fraction, so the final selection of the perforation fraction should be done considering the mechanical integrity during the fabrication condition.

UO_2-Mo, the resulting multilayer approximately doubles the radial effective conductivity at a metal loading of about 3 vol%, corresponding to a centerline temperature reduction of ~250 K at representative linear power.

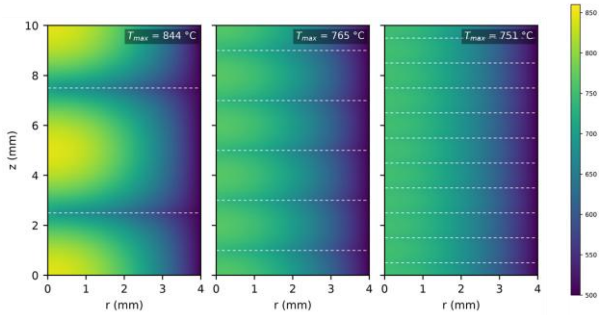


Fig. 3. Axial temperature profile of UO_2 pellet containing 2.5 vol.% Mo, 20% perforation fraction, with varying the number of Mo layers.

2.3 Verification using surrogate material

Verification of thermal conductivity enhancement was conducted using CeO_2 as a UO_2 surrogate. Multilayer compacts with perforated Mo layers are consolidated by spark plasma sintering. Cross-sectional electron microscopy of the Mo layer-oxide interfaces and sintered bridges, and thermal conductivity measurement in the radial (in-plane) and axial (series) directions were followed.

3. Conclusions

A perforated metal multilayer UO_2 pellet was proposed including sintered bridges resolve the two failures of multilayer concept: shrinkage-mismatch cracking and the unbonded metal-oxide interface. Design analyses optimized perforation shape, number of layers, perforation fraction. Calculation results showed an approximately twofold radial conductivity gain with ~3 vol.% of metal, beyond the theoretical upper bound of isotropic microstructures. Surrogate fabrication and characterization results supports the feasibility of the concept. This results is expected to contribute to the enhanced safety and performance of UO_2 fuel.

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