Development of a Fabrication Process for Annular Metal Fuel

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1. Introduction

The development of advanced nuclear fuel technology is crucial for enhancing the efficiency, safety, and sustainability of next-generation nuclear reactors. Metallic fuels, particularly uranium-zirconium (U-Zr) alloys, have gained attention due to their high thermal conductivity, superior fissile density, and potential for improved reactor performance.

Despite these advantages, metal fuels also pose challenges. Their relatively low melting point requires effective heat transfer mechanisms to maintain thermal margins. Additionally, metallic fuels exhibit swelling during irradiation, leading to potential fuel-cladding interaction (FCI) and reduced operational lifetimes. To address these issue sodium bonding should be required, which could potentially reduce the fuel fabrication yield. Annular metal fuel has been proposed as an innovative solution. Annular fuel features a hollow cylindrical geometry, which could maintain enough heat transfer efficiency with minimizing FCI [1, 2].

The fabrication of annular metal fuel requires precise and reliable manufacturing methods. Among the most studied fabrication techniques are injection casing, compact sintering, spark plasma sintering (SPS). This study integrates findings from research on these fabrication methods, evaluating their feasibility, efficiency, and material properties for manufacturing high-performance annular metal fuel.

2. Methods

2.1 *Injection Casting*

Injection casting is a well-established method for fabricating metallic fuels with high density and minimal defects. The process involves selecting quartz molds with an outer diameter of 6.40 mm and an inner diameter of 3.00 mm, coating them internally with Y_2O_3 to prevent adhesion and reaction with molten metal, and adding internal mold supports to prevent eccentricity and ensure uniform fuel geometry. The U-10wt.%Zr alloy is melted under a high vacuum (4.0×10^{-5} torr) to prevent oxidation and contamination, then injected into the mold using high-pressure argon gas. The mold is maintained at controlled temperatures to allow uniform solidification. Once the molten metal has cooled at room temperature, defects such as shrinkage cavities and eccentricity are analyzed using cross-sectional imaging.

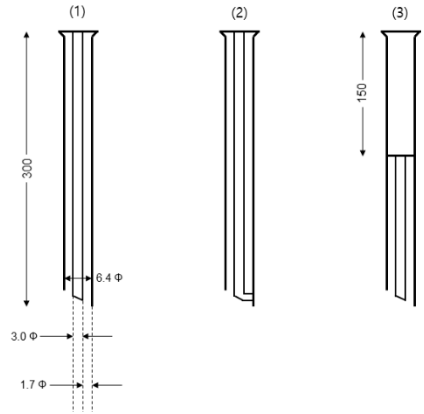

Fig. 1. Design of the quartz mold for annular fuel fabrication.

2.2 Compact Sintering

Compact sintering is a versatile fabrication technique that allows precise microstructural control. The process begins with the preparation of U-10wt.%Zr powders using the hydride-dehydride method [3], ensuring fine and uniform particle distribution between 1 to 30 μm. Zirconium powder (100-150 μm) is mixed with uranium powder at a 9:1 weight ratio. The mixed powder is then cold-pressed into annular molds under a pressure of 20 MPa for 1 minute. Due to uranium powder's low viscosity, the compacted green pellets have low mechanical strength and require immediate sintering. The compacts are then sintered in an argon atmosphere (20 ml/min) at temperatures ranging from 800 to 1100°C for 8 hours.

2.3 Spark Plasma Sintering (SPS)

Spark plasma sintering (SPS) is an advanced sintering technique that enhances densification while minimizing processing time. The process involves mixing U-10wt.%Zr powders in a controlled ratio, similar to compact sintering, and testing three types of zirconium powders to optimize sintering behavior. The powder mixture is placed in graphite molds designed for annular pellets, wrapped in graphite paper to facilitate ejection, and processed in a vacuum of 1×10^{-2} torr. A pulsed DC current is applied while maintaining a pressure of 20 MPa for 5 minutes, with sintering temperatures ranging from 600 to 900°C.

3. Results

The fabrication results reveal significant differences in the physical properties of the annular fuel produced by each method. Injection casting produces the highest-density fuel with minimal porosity, achieving over 95% of the theoretical density. However, process defects such as shrinkage cavities, eccentric fuel, and mold deformation require optimization. Compact sintering results in lower densities, ranging between 55-70%, and exhibits high porosity due to the sintering limitations of zirconium. In contrast, SPS is able to produce pellets with a density of 74-90%, demonstrating improved densification compared to conventional compact sintering.

Fig. 2. Fabricated annular fuel using injection casting

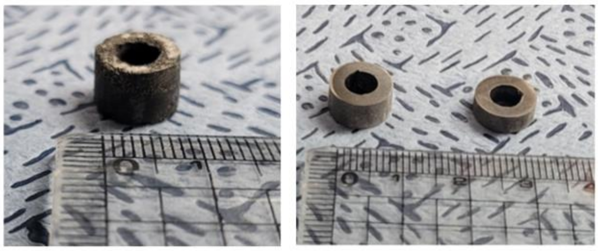

Fig. 3. U-10Zr pellet fabricated by compact sintering (left) and SPS (right)

Additional microstructural analyses using SEM and XRD confirm that injection-cast fuels have a uniform phase distribution with minimal defects, while compact sintering samples show noticeable porosity and incomplete zirconium integration. The SPS method results in well-dispersed zirconium within the uranium matrix, with fewer voids and a more homogeneous microstructure.

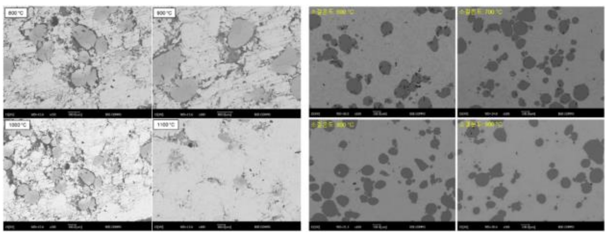

Fig. 4. SEM image of U-10Zr pellet fabricated by compact sintering (left) and SPS (right)

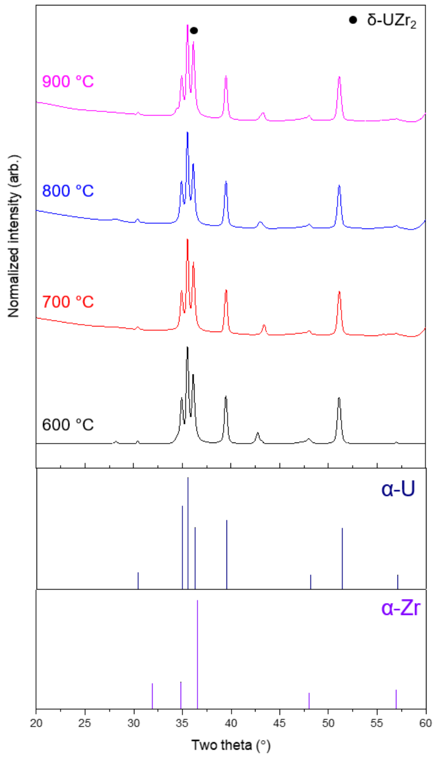

Fig. 5. XRD analysis on as-sintered U-10Zr fuel pellet fabricated by SPS

Table 1. Detail comparison of each fabrication method.

Fabrication Method	Injection Casting	Compact Sintering	SPS
Density (%TD)	>95%	55-70%	74-93%
Processing Time	Medium (30 min ~ 1 hour)	Long (>8 hours)	Short (<5 minutes)
Key Advantages	High density, minimal porosity, good productivity	Simple setup, fine microstructural control	Low porosity, high densification in short time
Key Challenges	Potential shrinkage defects, eccentric hole	High porosity, poor densification at low temperatures	Requires specialized equipment, limited large-scale production

3. Conclusion

This study compares three fabrication methods—Injection Casting, Compact Sintering, and Spark Plasma Sintering—for producing annular metal fuel with a U-10wt.%Zr composition. Injection casting demonstrates the highest density and defect minimization but requires precise mold handling. Compact sintering, while offering microstructural control, suffers from poor densification. SPS emerges as a promising technique for achieving high-density fuel with reduced porosity, but its industrial scalability remains a challenge.

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