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Volatile Elements Retention during Injection Casting of Metallic Fuel Slug for a Recycling Fast Reactor

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1. Introduction

Metallic fuel for a recycling fast reactor has advantages such as simple fabrication procedures, good neutron economy, high thermal conductivity, and excellent compatibility with a Na coolant [1].

For several decades, the fabrication technology of metal fuel has been developed by various methods such as rolling, swaging, wire drawing, and co-extrusion, but each of these methods had process limitations requiring an additional subsequent process, and needing the fabrication equipment is complex, which is not favorable for remote use. A practical process of metallic fuel fabrication for an SFR needs to be cost efficient, suitable for remote operation, and capable of mass production while reducing the amount of radioactive waste. Injection casting was chosen as the most promising technique, and this technique has been applied to fuel slug fabrication for the Experimental Breeder Reactor-II (EBR-II) driver and the Fast Flux Test Facility (FFTF) fuel pins. Because of the simplistic nature of the process and equipment, compared to other processes examined, this process has been successfully used in a remote operation environment for fueling of the EBR-II reactor.

In this study, several injection casting methods were applied in order to prepare metallic fuel for an fast reactor that control the transport of volatile elements during fuel melting and casting. Mn was selected as a surrogate alloy since it possesses a total vapor pressure equivalent to that of a volatile minor actinide-bearing fuel. U–10Zr and U–10Zr–5Mn (wt%) metallic fuels were injection cast under various casting conditions and their soundness was characterized.

2. Experimental Procedures

The lumps of depleted uranium, Mn, and sponge zirconium were weighed in proportion to the alloy compositions and charged into a melting crucible to fabricate fuel slugs. Zirconium was loaded into the bottom of the graphite crucible followed by Mn and uranium. The idea was to allow the lower-temperature melting material to flow over and consume the other alloy. The graphite crucible and quartz molds were coated with Y_2O_3 to protect them against reactions with the uranium alloy melt. This selection was done on the basis of the free energy needed for oxide formation. Graphite insulation was wrapped around the crucible to prevent any significant heat loss to the induction coil and furnace chamber.

Figure 1 shows the induction copper coil used in this experiment. The furnace was designed to rotate the upper chamber for easy separation of the mold assembly before and after casting. Injection casting uses the pressure difference between the mold's interior and the furnace's gas pressure to drive the molten metal up into the quartz tube, and it works under either a dynamic vacuum or a low-pressure argon atmosphere.

The casting alloys were heated by induction heating at a frequency of 3 kHz and a maximum power of 30 kW in the upper chamber. When the crucible temperature reached approximately 200℃ higher than the melting point, the alloy melt was held and stirred electromagnetically by applying an induction heating cycle from 0% to 100% to ensure the homogeneity of the melt. The flow of the molten material was driven into the quartz mold by the pressure of argon. Table 1 lists the experiment parameters and respective furnace pressures.

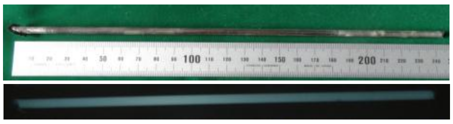
After solidifying the melt in the quartz mold, the metallic fuel slug was removed from the mold. Fuel slugs were cut into slices of suitable thickness using a slow-speed SiC abrasive cut-off wheel and the density at each location was measured using Archimedes' principle. The microstructures and compositions were analyzed using scanning electron microscope (SEM) with energy dispersive X-ray spectroscope (EDS). Casting yields and fuel losses were evaluated by measuring the material balance before and after casting.

Fig. 1. Induction copper coil used for heating the raw materials.

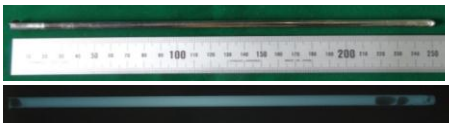
3. Results and Discussion

Figure 2 shows photographs and gamma radiographs of the U–Zr and U–Zr–Mn fuel slugs fabricated by injection casting under various casting conditions. The surfaces at the middle and upper regions of the slugs are smooth and the surfaces are somewhat rough at the lower region where the quartz mold merged with the melt and some reaction layers are observed. However, the as-cast slugs are generally sound and the length is the full size of the mold.

Inductively coupled plasma atomic emission spectroscopy (ICP-AES) was used to investigate the chemical composition of the fuel slugs quantitatively. Figure 7 shows the variations of U, Zr, and Mn content according to the position measured in the U–Zr–Mn fuel slug. The U, Zr, and Mn contents were homogeneous at the lower, middle, and upper positions of the fuel slug. However, it can be seen that the U content increased in the fuel slug fabricated in test *c* because the fraction of Mn was decreased by vaporization, which resulted in an increase of the slug density.



(a)



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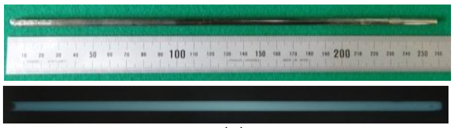
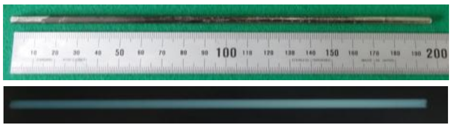


(c)



(d)

Fig. 2. Photographs and gamma radiographs of the U–Zr and U–Zr–Mn fuel slugs fabricated by injection casting under various casting conditions: (a) test *a*, (b) test *b*, (c) test *c*, and (d) test *d*

Table 1 Experimental parameters for injection casting of metal fuel slugs

	Test *a*	Test *b*	Test *c*	Test *d*
Charge alloy compositions	U–10Zr	U–10Zr–5Mn	U–10Zr–5Mn	U–10Zr–5Mn
Casting temperature (℃)	1530	1530	1530	1530
Injection pressure (kgf/cm^2)	110	120	150	200
Chamber atmosphere before injection	Dynamic vacuum condition	Ar (300 Torr) + Dynamic pumping condition (20 s)	Dynamic vacuum condition	Ar (300 Torr)
Holding time (sec)	4	4	4	4
Emerging time (sec)	9	9	9	9

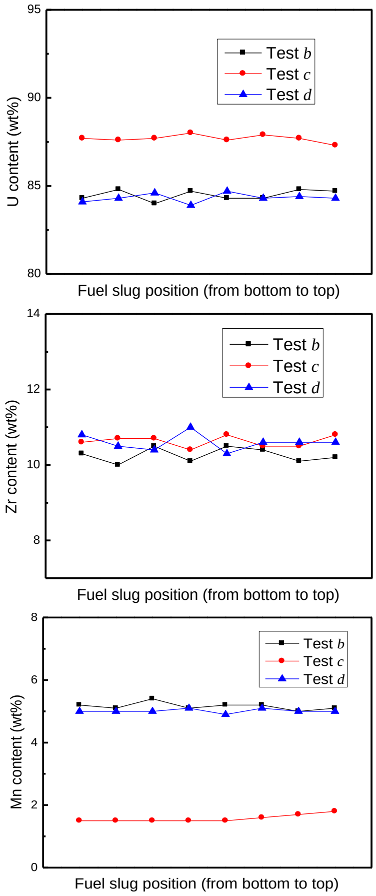


Fig. 3. Variations of chemical composition according to the position of a U–Zr–Mn fuel slug fabricated under different injection casting conditions: (a) U, (b) Zr, and (c) Mn

4. Conclusions

The as-cast fuels prepared by injection casting were sound and the internal integrities were found to be satisfactory through gamma-ray radiography. U and Zr were uniform throughout the matrix of the slug, and the impurities, i.e., oxygen, carbon, and nitrogen, satisfied the specification of the total impurities of less than 2000 ppm. The U–Zr fuel slug fabricated under dynamic vacuum conditions showed no element loss by vaporization, but the U–Zr–Mn fuel slug showed a loss of Mn of approximately 68% under the same injection conditions. The losses of the volatile Mn were effectively controlled using argon overpressures, and dynamic pumping for a period of time before injection showed no detrimental effect on the Mn loss by vaporization. This result suggests that volatile minor actinide-bearing fuels for SFRs can be prepared by improved injection methods.

5. References

[1] G.L. Hofman, L.C. Walters, T.H. Bauer, Metallic Fast Reactor Fuels, Progress in Nuclear Energy, Vol.31, p.83, 1997.