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Modified Fabrication Method of Metal Fuel Slug for Preventing Evaporation of Volatile Elements

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1. Introduction

Metal fuels such as U-Zr/U-Pu-Zr alloys have been considered as a nuclear fuel for a sodium-cooled fast reactor (SFR) related to the closed fuel cycle for managing minor actinides and reducing a high radioactivity levels since the 1980s.1-2 In order to develop innovative fabrication method of metal fuel slugs for preventing the evaporation of volatile elements such as Am, modified casting under inert atmosphere has been applied for metal fuel slugs for SFR.3-4 Alternative fabrication method of fuel slugs has been introduced to develop an improved fabrication process of metal fuel for preventing the evaporation of volatile elements. In this study, U-10wt.%Zr-Mn fuel slugs for SFR have been fabricated by modified casting method and characterized to evaluate the feasibility of the alternative fabrication method.

2. Experimental Procedures

Elemental lumps of depleted uranium, zirconium, manganese as a surrogate of volatile Am, and rare-earth elements were used to fabricate U-10wt.%Zr-5wt.%Mn fuel slug by modified casting method. Mn was selected as a volatile surrogate alloy since it possesses an equivalent total vapor pressure to the minor actinide-bearing fuel. Graphite crucibles coated with high-temperature ceramic plasma-spray coating and quartz molds coated with high-temperature ceramic by slurry-coating were used. Various casting variables, e.g., casting temperature and pressure, pressurizing rate, mold coating method were adjusted in modified casting process. At a predetermined superheat, the mold was lowered, immersing the open tip into the metal melt. U-10wt.%Zr-Mn fuel slugs were fabricated by modified casting method. Metallic fuel alloys containing volatile radioactive constituents, such as Am, is problematic in the conventional injection casting method, because the furnace containing the fuel melt is evacuated. Mn element was used for surrogate for Am radioactive constituents. The casting stage commences with the application of vacuum in order to evacuate the molds which are then inserted into the melt. The evaporation of Mn element depends on the time applied to vacuum during casting process.

After fabricating the fuel slug in the casting furnace, the fuel losses in the crucible assembly and the mold assembly were quantitatively evaluated after casting of the fuel slug under vacuum state and inert atmosphere. The soundness and the chemical composition of as-cast fuel slug were identified and analyzed. As-cast fuel slug were inspected in casting soundness by gamma-ray radiography. The densities of the fuel slug were also measured by Archimedean immersion method. A scanning electron microscope (SEM) was used to study the microstructure of as-cast fuel slug. Chemical compositions of as-cast fuel slugs were measured by energy-dispersive spectroscopy (EDS).

3. Results and discussion

U-10wt.%Zr-Mn fuel slugs was soundly fabricated with dimensions of Φ5 – L250mm by modified injection casting method, as shown in Fig. 1. General appearance of the slug was smooth and the length was about 250mm. Gamma-ray radiography of as-cast U-10wt.%Zr-Mn fuel slug was performed to detect internal defects such as cracks and pores. Internal integrity of as-cast metal fuel slug in lower part was generally satisfactory.

(a)

(b)

Fig. 1. U-10wt%Zr-5wt.%Mn fuel slug (Φ5 mm x L250 mm) (a), and gamma-ray radiography (b), fabricated by modified injection casting.

Fuel loss during vacuum injection casting of U-10wt.%Zr-Mn fuel slug was considerable upto 2.6% due to considerable evaporation of volatile surrogate Mn under vacuum state. Fuel loss of U-10wt.%Zr-Mn fuel slug was so low, about 0.2% due to prevention of Mn evaporation in case of alternative casting, as shown in Table 1. Modified injection casting had lower fuel loss than vacuum injection casting. Table 2 shows alloy compositions and loss characteristics of U-10wt.%Zr-Mn fuel slug fabricated with vacuum injection casting and modified injection casting. There was a lot of Mn loss under vacuum injection casting condition. Mn element was most recovered with prevention in evaporation with modified injection casting under inert atmosphere. Volatile elements such as Am could be effectively controlled to below detectable levels using modest argon overpressures. It is thought that a lower fuel loss in case of casting of U-10wt.%Zr-Mn fuel slugs was related to melting of the U-10wt.%Zr-Mn alloy in a densely plasma-sprayed graphite crucible with high-temperature ceramic materials. Mn element was most recovered with the prevention in evaporation of the volatile surrogate, Mn. It was seen that the losses of these volatile elements such as Am can be effectively controlled to below detectable levels using modest argon overpressures. Fig. 2 shows scanning electron micrographs and energy-dispersive electron X-ray spectroscopies of U-10wt.%Zr-5wt.%Mn fuel slug, respectively. The microchemical analysis revealed a higher level of Mn content within the hypereutectic dendrite phases compared with eutectic phases of matrix.

Table 1. Material balance after casting of U-10wt.%Zr-5wt.%Mn fuel slug.

	Melting/casting part	Mass (g)	Fraction (%)
Before casting	Crucible	608.2	100.0
After casting	Crucible assembly	541.0	89.0
After casting	Mold assembly	65.9	10.8
Fuel loss		1.1	0.2

Table 2. Alloy compositions and loss characteristics of U-10wt.%Zr-5wt.%Mn fuel slug.

Item \ Casting Method		Vacuum injection casting	Modified injection casting
Alloy Composi-tion	U (wt.%)	88.1	84.9
	Zr (wt.%)	10.7	10.7
	Mn(wt.%)	1.6	5.0
	C (ppm)	53	66
	O (ppm)	951	652
	N (ppm)	16	10
	Si (ppm)	288	269
Density (g/cm^3)		15.2	14.8
Fuel loss (%)		2.6	0.2
Evaporation ratio of Mn element (%)		68	0

4. Conclusions

Alternative casting such as modified casting has been applied to develop fabrication method of fuel slugs for preventing the evaporation of volatile elements such as Am. U-10wt.%Zr-Mn containing a volatile surrogate Mn fuel slug was soundly fabricated under inert atmosphere with dimensions of Φ5 – L250mm. Mass fraction of fuel loss was so low, upto 0.2%. Mn element was most recovered with prevention in evaporation of Mn. It was seen that the losses of volatile Am can be effectively controlled to below detectable levels using modest pressure.

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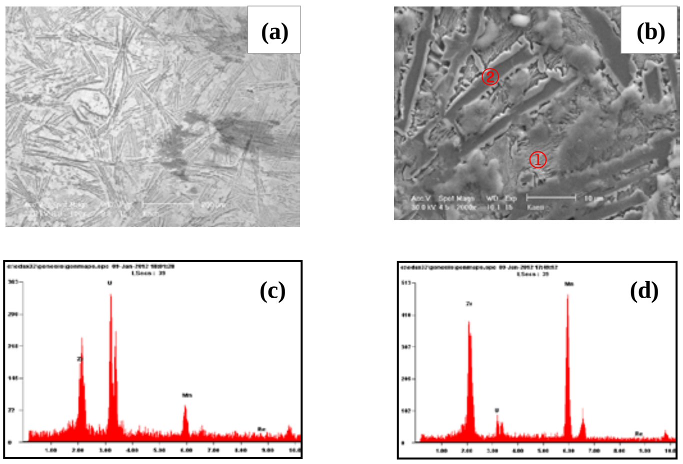

Fig. 2. Scanning electron micrographs of U-10wt.%Zr-5wt.%Mn fuel slug; and energy-dispersive electron X-ray spectroscopies of (a); (a) x100, (b) x2000, (c) matrix phase and (d) dispersive phase