FABRICATION OF SFR FUEL RODLETS FOR IRRADIATION TEST IN THE HANARO

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1 Introduction

KAERI seeks to develop and demonstrate the technologies needed to transmute the long-lived transuranic actinide isotopes in spent nuclear fuel into shorter-lived fission products, thereby dramatically decreasing the volume material requiring disposal and the long-term radio-toxicity and heat load of high level waste sent to a geological repository [1]. Metallic fuel has advantages such as simple fabrication procedures, good neutron economy, high thermal conductivity, excellent compatibility with a Na coolant and inherent passive safety [2-5]. U-Zr-Pu alloy fuels have been used for SFR (sodium-cooled fast reactor) related to the closed fuel cycle for managing minor actinides and reducing high radioactivity levels since the 1980s. Fabrication technology of metallic fuel for SFR has been in development in Korea as a national nuclear R&D program since 2007 [6-9]. The irradiation test of U-10wt.%Zr and U-10wt.%Zr-5wt.%Ce fuels in the HANARO has been planned to evaluate irradiation capsule integrity and to validate in-reactor barrier performance. The fuel rodlets of U-10wt.%Zr and U-10wt.%Zr-5wt.%Ce fuels have been fabricated for the irradiation test of SFR fuel in the HANARO. The process flow diagram of the metallic fuel rodlet is shown in Fig. 1. The fabrication of the metallic fuel rodlets will be discussed in this paper.

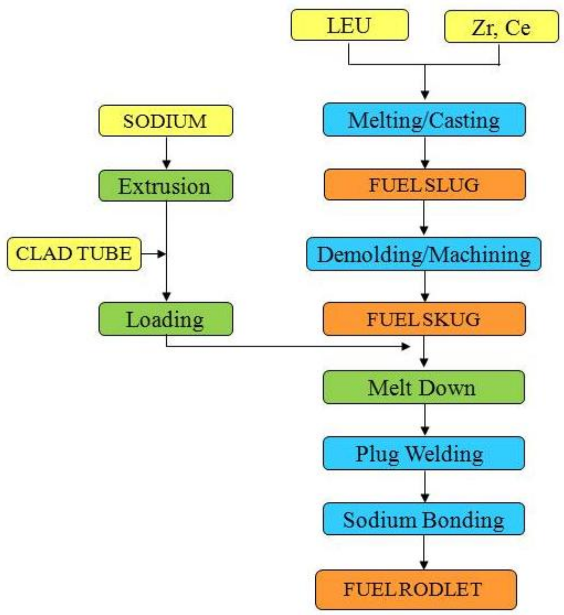


Fig. 1. Process flow diagram of metallic fuel rodlet.

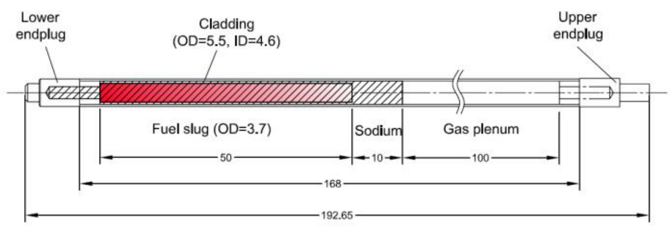


Fig. 2. A schematic diagram of the fuel rodlets for the irradiation test.

2 Experimental Procedure

Fig. shows a schematic diagram of the fuel rodlets for the irradiation test. The rodlet with a 193 mm length consists of fuel slug, cladding, and end plugs. The fuel slug is contained in the cladding where sodi -um is charged in between. Fuel slugs are U-10wt.%Zr and U-10wt.%Zr-5wt.%Ce, and have a diameter of 3.7 mm and a length of 50 mm. The claddings with an outer diameter of 5.5 mm and inner diameter of 4.6mm were fabricated with a ferritic-martensitic steel, T92 (9Cr0.5Mo2WV Nb). Sodium is covered up to the level of 10 mm higher than the upper end of the fuel slugs. The mass of the sodium is 0.5 g. The length of the free volume of the rodlet is 100 mm. Each rodlet is individually sealed in an outer sealing tube.

Fig. 3 shows the fuel slug fabrication equipment melted under Ar inert atmosphere. Elemental lumps of low-enrichment uranium (LEU), zirconium, and cerium were used to fabricate U-10wt.%Zr and U-10wt.%Zr-5wt.%Ce fuel slugs. Graphite crucible plasma-spray coated with Y_2O_3 was used [10-12]. Graphite and quartz were used as mold materials. After casting the metal fuel slugs, the fuel slugs were machined into the pin of 3.7mm in diameter

Fig. 3. Gravity casting furnace.

and 50mm in length using a lath with a diamond bite. As-cast fuel slugs were inspected by gamma radiography. The microstructure and phase were analyzed by using a scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS).

Sodium loading and settling were carried out in a glove box under Ar atmosphere. A sodium wire and a fuel slug were subsequently loaded into a jacket. The jackets were loaded into a settling furnace, heated to above 300^{o}C, and held at this temperature to settle the fuel slugs into the molten sodium within the jackets. The fuel rods were closed by insertion and welding of the end plugs. After an electron-beam welding, the claddings were checked visually, and examined for microstructure and mechanical properties, which resulted in establishing optimum welding conditions for the jacket. Sodium bonding is the process of wetting sodium to the fuel slug and cladding and removing any voids present in the annulus (the region between the fuel slug and cladding). The lower end of the fuel rod in the bonder magazine rested on an impact plunger. Thus, the fuel rodlets of U-10wt.%Zr and U-10wt.%Zr-5wt.%Ce fuels have been fabricated for the irradiation test of SFR fuel, as shown in Fig. 4.

Fig. 4. Metallic fuel rodlets, fabricated for irradiation test in the HANARO.

3 Results and Discussion

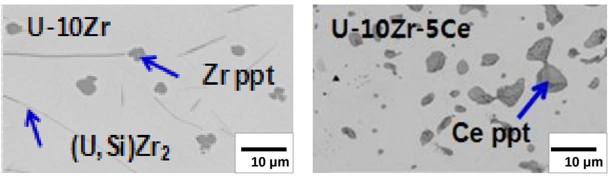
The sound U-10wt.%Zr and U-10wt.%Zr-5wt.%Ce fuel slugs could be fabricated by adjusting the melting process parameters. The metal fuel slugs were cast with the gravity casting furnace under Ar atmosphere, as shown in Fig. 5. The surface roughness was coarse, and a few defects were observed on the fuel surface, but the as-cast fuel slugs were generally sound. The metal fuel slug had the diameter of 4.2mm and the length of about 150mm. The alloy composition of the metal fuel slugs were shown in Table 1.

Fig. 5. Typical metal fuel slugs cast by gravity casting method under Ar atmosphere.

Table 1. Alloy compositions of metallic fuel slugs.

Nominal Composition	Zr (wt.%)	Ce (wt.%)	C (ppm)	H (ppm)	O (ppm)	N (ppm)
U-10Zr	9.8	-	110	22	470	10
U-10Zr-5Ce	11.5	5.2	450	25	370	40

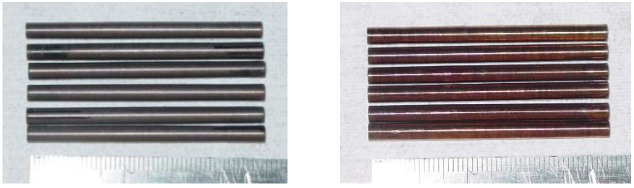
Scanning electron micrographs of the fuel slugs were shown in Fig. 6. U-10wt.%Zr fuel slugs had some dispersion phases of Zr precipitates and Zr compounds, and U-10wt.%Zr-5wt.%Ce fuel slugs had lots of dispersion particles including Ce component, distributed in the homogeneous and fine state in U-10wt.%Zr-5wt.%Ce alloy. U-10wt.%Zr and U-10wt.%Zr-5wt.%Ce fuel slugs showed fine laminar structure, irrespective of alloy composition. The major alloy phases of the U-10wt.%Zr alloy were α-U and δ-UZr_2. The microstructure showed a laminar structure with fiber morphology which was arranged alternatively with uranium and Zr-rich phase. Major alloy phases of U-10wt.%Zr-5wt.%Ce alloy were α-U and δ-UZr_2 similar to U-10wt.%Zr alloy. Matrix of U-10wt.%Zr-5wt.%Ce alloy was not modified by the addition of Ce element, and illustrated a laminar structure which is beneficial to a fast fission gas release. The laminar structure of the U-10wt.%Zr-5wt.%Ce alloy was very fine, similar to that of U-10wt.%Zr alloy. The refinement in the laminar structure of the U-10wt.%Zr-5wt.%Ce alloy could greatly increase the release rate of gas bubble, due to well inter-connected path of fission gas bubble with metal fuel for SFR. In addition, it is expected to contribute in preventing the swelling of metallic fuel caused by a bubble-driven swelling mechanism.



(a) (b)

Fig. 6. Scanning electron micrographs of the fuel slugs; (a) U-10wt.%Zr, (b) U-10wt.%Zr-5wt.%Ce.

After casting, the metal fuel slugs were machined into a slug of 3.7mm in diameter and 50mm in length by a lath, as shown in Fig. 7. Gamma radiography was also performed to detect internal defects such as cracks and pores of the metallic fuel slugs. The gamma radiography results are shown in Fig. 8. Internal pores were detected in some fuel slugs. However, the internal integrity of as-cast metallic fuel slugs is generally believed to be satisfactory.



(a) (b)

Fig. 7. Machined fuel slugs after gravity casting under Ar atmosphere; (a) U-10wt.%Zr,(b) U-10wt.%Zr-5wt.%Ce.

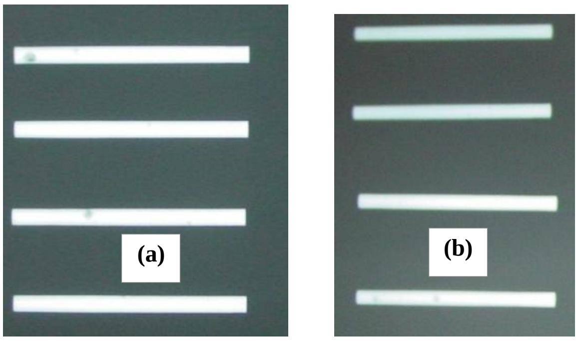
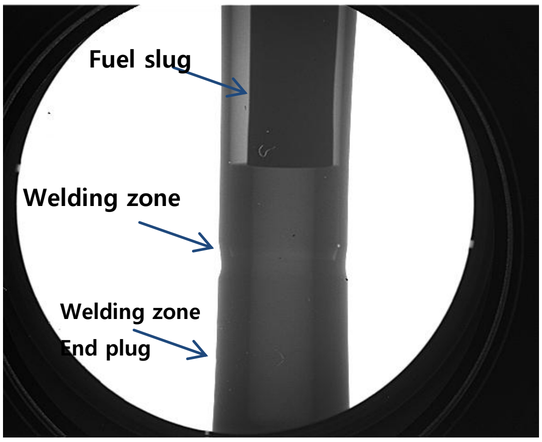


Fig. 8. γ-ray radiographs of the fuel slugs; (a) U-10wt.%Zr, (b) U-10wt.%Zr-5wt.%Ce.

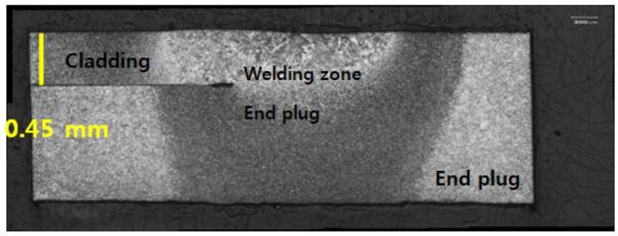
The plugs of the fuel rodlets were welded with the optimum welding parameters under vacuum by an electron beam welding equipment. Examinations of the X-ray radiography and the microstructure on the fuel rodlets after the electron beam were performed, as shown in Fig. 9. Sodium bonding is the process of wetting sodium to the fuel slug and cladding and removing any voids present in the annulus (the region between the fuel slug and cladding), each of which ensures adequate heat transfer between the fuel and cladding. The lower end of the fuel rod in the bonder magazine rested on an impact plunger. The bonder magazine was soundly bonded at about 500^{o}C, as shown in Fig. 10. The fuel rod displacement was set to a specific range to provide the necessary amount of energy for sodium bonding without damaging the rod. Thus, the fuel rodlets of U-10wt.%Zr and U-10wt.%Zr-Ce fuels have been fabricated for the irradiation test of SFR fuel.

4 Conclusions

U-10wt.%Zr and U-10wt.%Zr-5wt.%Ce fuel slugs were cast using low-enrichment uranium (LEU) with



(a)



(b)

Fig. 9. X-ray radiograph (a) and microstructure (b) of the fuel rodlet after electron beam welding.

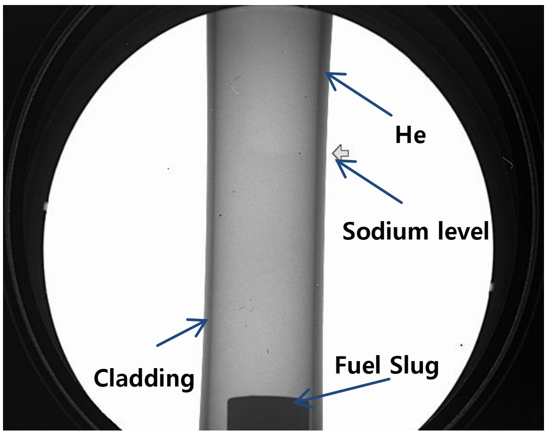


Fig. 10. X-ray radiographs of the fuel rodlets after sodium bonding.

the gravity casting furnace under Ar atmosphere. Visual inspection, gamma-radiography, micro-structure analysis, and density measurement were performed. The internal integrity of as-cast U-10wt.%Zr and U-10wt.%Zr-5wt.%Ce metallic fuel slugs was overally sound even if a few internal defects were observed in some fuel slugs. The effects of Ce element additions on the characteristics of U-10wt.%Zr Alloy were investigated. The disperse precipitates containing Ce element in U-10wt.%Zr-5wt.%Ce alloy were homogeneously and finely distributed. Some precipitates, identified as Zr-rich precipitates, were observed in the U-10wt.%Zr-5wt.%Ce fuel matrix. A laminar structure with a thickness of about 0.2μm was observed in the matrix for U-10wt.%Zr-5wt.%Ce fuel slugs. Sodium settling and bonding were carried out with a sodium furnace in Ar atmosphere glove box. The plugs of the fuel rodlets were welded with the optimum welding parameters under vacuum by an electron beam welding equipment. Hence, the fuel rodlets were soundly fabricated for the irradiation test of SFR fuel in the HANARO.

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