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Application of Ceramic Bond Coating for Reusable Melting Crucible of Metallic Fuel Slugs

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1. Introduction

U-Zr and U-TRU-RE-Zr metal fuel have been considered as the driver fuels for a Sodium-cooled Fast Reactor (SFR) in Korea [1-2]. Metal fuel slugs of the driver fuel assembly have been fabricated by injection casting of the fuel alloys under a vacuum state or an inert atmosphere [3-5]. Traditionally, metal fuel such as a U-Zr alloy system for SFR has been melted in slurry-coated graphite crucibles and cast in slurry-coated quartz tube molds to prevent melt/material interactions. Reactive coatings and porous coatings can be a source of melt contaminations, and fuel losses, respectively. A dense ceramic plasma-spray coating of non-reactive materials that does not require recoating is very desirable for a reusable crucible.

Ceramic Y_2O_3, TiC, and TaC coating materials showed no penetration in the protective layer after a melt dipping test. However, the ceramic coating materials showed separations in the coating interface between the substrate and coating layer, or between the coating layer and fuel melt after the dipping test. The issue of a thermal expansion mismatch between the coatings and crucibles must be overcome. In this study, various combinations of coating conditions including bond coating materials were investigated to find the bonding effect on the substrate and the interaction of metal fuel with a plasma-spray coated crucible substrate.

2. Methods and Results

Plasma-spray coating methods were applied to pure niobium rods with a diameter of 10 mm and graphite crucibles with a diameter of about 100 mm. Y_2O_3, TaC, and TiC powders, ranging from 10 to 45 μm in size, were plasma-spray coated with a protective atmosphere onto Nb rods and graphite crucibles. The coated rods were immersed in U-10wt.%Zr and U-10wt.%Zr-5wt.%RE (RE: rare-earth elements comprising 53 % Nd, 25% Ce, 16 % Pr, and 6 % La by weight) alloy melt contained in a coated graphite crucible under an inert atmosphere. Melt dipping tests were conducted in which the samples were lowered into the melt at 1600℃, and withdrawn and cooled outside the crucible in the inert atmosphere of the induction furnace.

Metal fuel slugs were fabricated using an injection casting method with a graphite crucible coated with promising coating materials. 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).

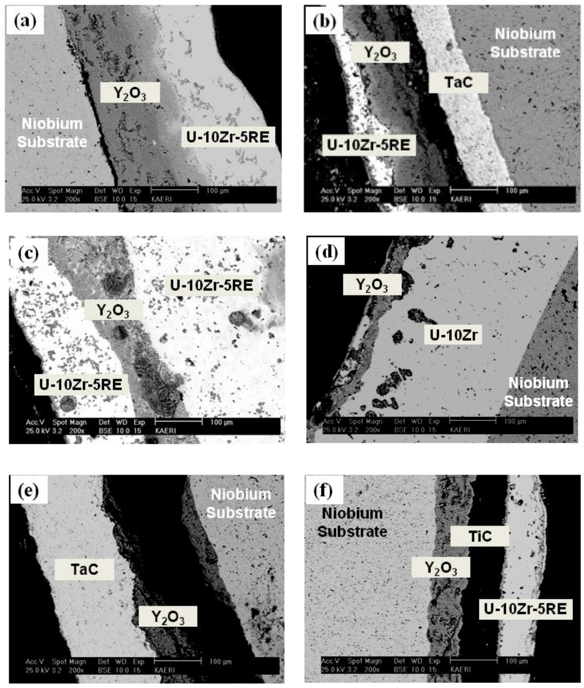
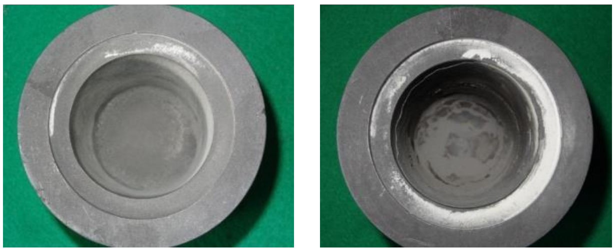


Fig. 1. Cross-sectional BSE micrographs showing the interface between U-10wt.%Zr-RE and coating layer after two cycles of dipping at 1600ºC for 5 min: (a) Y_2O_3(150), (b) TaC(50)-Y_2O_3(100), (c) Y_2O_3(50)-TaC(100), (d) Y_2O_3(50)-TiC (100), (e) Y_2O_3(100)-TaC(100)-Y_2O_3(100), and (f) Y_2O_3(100)-TiC(100)-Y_2O_3(100).

Fig. 1 shows the BSE micrographs of the coated specimens after two cycles of exposure to the U-10wt.%Zr-5wt.%RE melt. The Y_2O_3(150) vacuum plasma-spray (VPS) coated Nb substrate showed an interaction layer of about 50μm in thickness formed by a partial penetration of the Nd element in the melt into the Y_2O_3 coating layer, as shown in Fig. 1-(a). The double layer of TaC(50)-Y_2O_3(100) coated on the Nb substrate showed a similarly good result as a single layer coating with Y_2O_3, as shown in Fig. 1-(b). The double layer of Y_2O_3(50)-TaC(100), Y_2O_3(50)-TiC(100) and the triple layer of Y_2O_3 (100)-TiC(100)-Y_2O_3(100) coated on the Nb substrate showed heavy penetrations of U-10Zr-5RE melt onto the substrate through the cracks of the Y_2O_3 bonding layer and the TaC protective layer produced by the composite effect of thermal shock and the interaction of the RE elements, as shown in Fig. 1-(c), (d) and (f). Thus, a large amount of damage was observed in the double-layer coated rods. The triple layer of Y_2O_3(100)-TaC(100)-Y_2O_3(100) coated on the Nb substrate showed a separation in the interface between the substrate and Y_2O_3 bond, as shown in Fig. 1-(e).

Based on the results from the interactions with U-10wt.%Zr and U-10wt.%Zr-5wt.%RE melt, Y_2O_3(150) and TaC(100)-Y_2O_3(100) plasma-spray coating methods have been applied to the graphite crucible. Injection casting experiments of metal fuel slugs were then conducted to investigate the feasibility of the reuse in the plasma-spray coated graphite crucibles, as shown in Fig. 2. The general appearance of the U-10wt.%Zr fuel slug was smooth with a diameter of 5.4 mm and a length of about 250 mm after injection casting. The surface of the slug was smooth, and the roughness was a little coarse at the lower region. The gamma-ray radiography of the as-cast slug was performed to detect internal defects such as cracks and pores. Internal pores were not detected in the slugs, and thus the internal integrity of the as-cast slugs was generally believed to be satisfactory. The inner surface of the crucible was smooth, and the residue in the graphite crucible could be separated from the graphite crucible after injection casting. This indicates no reaction layer formation or penetration of U–10wt.%Zr melt into the coating. The graphite crucible was reused to fabricate a U-10wt.%Zr fuel slug after cleaning with a brush. The result after interaction of U-10wt.%Zr-5wt.%RE melt with coated graphite was similar to that after the interaction of the U-10Zr melt. Accordingly, the high-temperature ceramic plasma-spray coatings were thought to be promising candidate coating materials for a reusable graphite crucible to fabricate metal fuel slugs.



(a) (b)

Fig. 2. Used graphite crucibles coated with (a) Y_2O_3, and (b) TaC-Y_2O_3 after injection casting of U-10wt.%Zr-5wt.%RE fuel slug.

3. Conclusions

All plasma-spray coated methods maintained a sound coating state after a dipping test with U-10wt.%Zr melt. A single coating Y_2O_3(150) layer and double coating layer of TaC(50)-Y_2O_3(100), showed a sound state or little penetration in the protective layer after a dipping test with U-10wt.%Zr-5wt.%RE melt. The other plasma-spray coated layers showed the penetration of the fuel melt by cracking through the coating layers and separations in the coating interface after melt dipping test. Injection casting experiments of U-10wt.%Zr and U-10wt.%Zr-5wt.%RE fuel slugs have been performed to investigate the feasibility of a reusable crucible of the metal fuel slugs. U–10wt.%Zr and U–10wt.%Zr–5wt.%RE fuel slugs have been soundly fabricated without significant interactions of the graphite crucibles. Thus, the ceramic plasma-spray coatings are thought to be promising candidate coating methods for a reusable graphite crucible to fabricate metal fuel slugs.

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