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Cold Spray Coating Technique with FeCrAl Alloy Powder for Developing Accident Tolerant Fuel Cladding

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1. Introduction

Zirconium-based alloys show fairly good resistance to corrosion under the operating conditions of a pressurized- or boiling-water reactor (PWR or BWR), as well as a very low absorption cross section of thermal neutrons with limited irradiation growth and creep. These attractive properties make them well suited for use as nuclear fuel cladding and structural components in conventional light water reactors (LWRs). However, the aggressive oxidation and significant heat production of Zr-based alloys in a high-temperature steam environment could significantly increase the risk of explosion caused by hydrogen gas [1,2], as seen in the Fukushima nuclear reactor accident. As a result, issues regarding the safety of nuclear plants during severe accidents and natural disasters were raised and solutions were discussed [3,4]. Although various approaches to enhance safety have been suggested, replacing current Zr-based alloys for fuel cladding with advanced materials exhibiting lower oxidation rates can be a basic solution [5,6]. Many advanced materials such as FeCrAl alloys; Mn+1AXn, (MAX) phases, where n = 1 to 3, M is an early transition metal, A is an A-group (mostly IIIA and IVA, or groups 13 and 14) element and X is either carbon or nitrogen [7]; Mo [8]; and SiC [9,10] are being considered as possible candidates.

Among the proposed fuel cladding substitutes, Fe-based alloys are one of the most promising candidates owing to their excellent formability, high strength, and oxidation resistance at high temperature. In this work, the ATF technology concept of Fe-based alloy coating on the existing Zr-alloy cladding was considered and results on the optimization study for fabrication of coated tube samples were described. Microstructural characterization study was carried out not only for as-fabricated tube samples but also for tube samples oxidized at high temperature.

2. Methods and Results

Cold spray coating process for Zr plate specimens was preliminary carried out before fabrication of FeCrAl layer coated ATF cladding sample. FeCrAl alloy powder (Sandvik Heating Technology AB, Hallstahammar, Sweden) and pure Mo powder were used in this study. This alloy consists of the main alloying elements and small amounts of additional alloying elements such as Si, Mn, and C. The nominal chemical composition (wt%) of the alloy is as follows: Cr, 22; Al, 5; Mo,3; Si, <0.7; Mn, <0.4; C, <0.05; Fe, balance.

Fig. 1 shows cross-sectional cut of FeCrAl alloy and Mo layer coated Zr plate sample. The thickness of the FeCrAl alloy coating varies between 30 and 65 μm with an average value of 50 μm. No gap was observed between coating and substrate indicating good scale adherence. However, individual particles of different sizes can be recognized and a few voids were observed in the outer region of coated FeCrAl alloy layers.

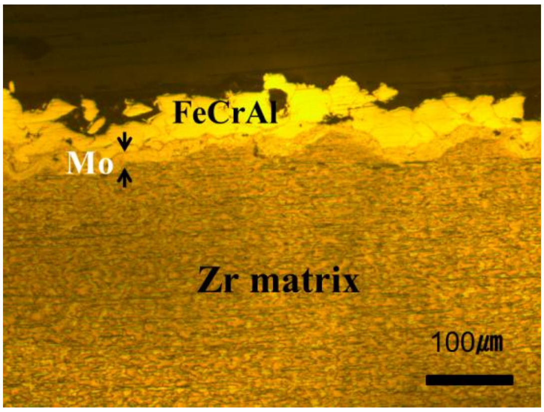

Fig. 1. Cross-sectional optical microscopy image of Multi layers coated Zr plate sample.

To investigate the suitability of cold sprayed FeCrAl coatings as oxidation barrier, high temperature oxidation test was conducted at 1200℃ for 3000s in a steam environment. As shown in Fig. 2(a) uncoated sample showed a thick oxide layer on the surface after oxidation. The average oxide thickness was approximately 121.7 μm and oxygen stabilized a Zr phase was also formed just under oxide layer since the oxygen diffused from the oxide layer. In contrast, for the FeCrAl coated Zr sample, oxides couldn’t be observed by using optical microscopy. Therefore, it can be concluded that FeCrAl alloy layer coated by cold spray technique is suitable for oxidation barrier of Zr-based alloy.

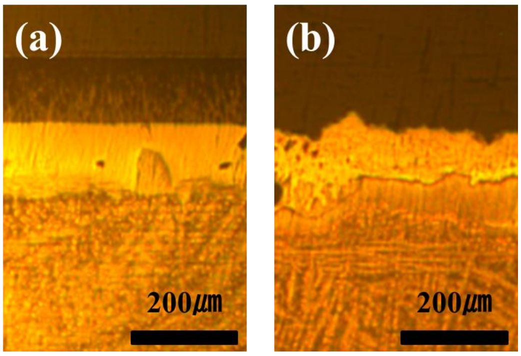

Fig. 2. Cross-sectional optical microscopy image of (a) uncoated and (b) coated Zr plate sample after oxidation at 1200℃ for 3000s.

FeCrAl alloy coated cladding samples have been successfully fabricated by using existing Zr alloy fuel claddings. Fig. 3(a) shows 500 mm long Zr fuel claddings having a cold sprayed FeCrAl coating on their surface. In this case, coated region was 450 mm long. As shown in Fig. 3(b), the thickness of the FeCrAl alloy coating varies between 40.5 and 88.8 μm with an average value of 61.5 μm. Morphology and appearance of coating layer did not change significantly with position. The outer surface of coated layer was uneven and boundaries in the coating layer caused by each coated FeCrAl alloy powder were observed.

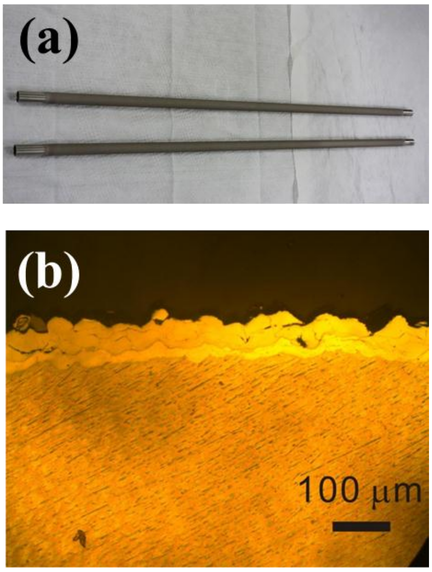

Fig. 3. FeCrAl alloy coated Zr cladding with coating region of 450 mm and its cross-sectional optical microscopy image.

3. Conclusions

FeCrAl alloy coated Zr tube sample was successfully manufactured with good adhesion between both layers. Mo inter layer has prevented inter-diffusion between FeCrAl and Zr matrix after high temperature exposure. Result obtained from high temperature oxidation test under steam environment at 1200℃ indicates that FeCrAl alloy coated Zr metal matrix may maintain its integrity during LOCA. This means that accident tolerance of FeCrAl alloy coated Zr cladding sample had been greatly improved compared to that of existing Zr-based alloy fuel cladding.

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