Track 1: Advances in Nuclear Fuel Design and Fabrication

Overview on the Thermal and Mechanical Properties of HANA^{TM} Claddings

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Abstract

Zirconium-based alloys have been used as a fuel rod cladding material in light water reactor (LWR) since the early 1960s. But the pressures to achieve higher fuel burn-ups and higher reactor thermal efficiencies had pushed the historically used alloys, such as Zircaloy-4 and Zircaloy-2, to the limits of their capabilities. These limits provided with a motivation to develop advanced cladding materials. In the mid-1990s, Korea Atomic Energy Research Institute (KAERI) had commenced the project to develop the advanced Zr claddings, which were named HANA^{TM} claddings, for the higher burn-up fuel ($\geq$ 70,000 MWD/MTU). The performance tests of the HANA^{TM} claddings are being carried out to evaluate systematically their normal performances under the out-of-pile and in-pile conditions. From the corrosion results in PWR-simulated loop for 1000 days, the corrosion resistances of the HANA^{TM} claddings were superior to that of the reference commercial claddings (i.e., Zircaloy-4). And the HANA^{TM} claddings also showed the excellent in-pile performances in Halden reactor when compared with the reference commercial claddings. At a hold point of this stage, the utilization prospects of the HANA^{TM} claddings were considered on the based on their performances obtained from the out-of-pile and in-pile tests.

Since the alloying system of the HANA^{TM} claddings is quite different from that of the reference commercial cladding such as Zircaloy-4, the thermal and mechanical properties of the HANA^{TM} claddings should be required to demonstrate their reliabilities in the licensing process. A series of tests had been performed to evaluate the thermal and mechanical properties of the HANA^{TM} claddings. That is, the thermal and mechanical properties evaluated for the HANA^{TM} claddings were listed as followings; density, thermal expansion, specific heat, thermal conductivity, surface emissivity, phase transformation temperature, melting point, Young's modulus, Poisson ratio, lattice parameter, and texture parameter. Only three HANA^{TM} claddings (HANA-4, HANA-5, and HANA-6) were focused on the evaluation works although six types of the HANA^{TM} claddings were originally manufactured as cladding tubes. Thus, this study includes the evaluation results of the thermal and mechanical

properties for three HANA^{TM} claddings and gives an analysis of the difference in the comparison with a reference cladding of Zircaloy-4.

The density of the HANA^{TM} claddings was determined by mass and volume measurements. The mass of the samples was measured at room temperature (25^{o}C) by using a precise mass measurement method, of which accuracy was less than 1.5%. The density of the HANA^{TM} claddings at 25^{o}C was ranged from 6.5349 to 6.5526 g/cm^3. These are comparable to that (6.5510 g/cm^3) of Zircaloy-4. Since the density change was linearly affected by the volume one, the density at any temperature can be obtained from the volume at that temperature. The precise volume was calculated from the true strains for any orthogonal coordination system. The thermal expansion coefficients of the HANA^{TM} claddings were also measured by using a thermal dilatometer for three cylindrical orientations of the axial, circumferential and radial directions at the temperatures between 25 and 1050^{o}C. The thermal expansion coefficients of the HANA^{TM} claddings were distinguished from the measuring orientations but did not show the difference in the cladding composition. And the specific heats of the HANA^{TM} claddings obtained from a differential scanning calorimetry were different from that of Zircaloy-4 due to their different chemical composition. The discontinuity of the specific heats for the HANA^{TM} claddings occurred at temperatures between 600 and 970^{o}C while that of the Zircaloy-4 occurred between 800 and 970^{o}C. This would be resulted from the Nb addition as a alloying element in HANA^{TM} claddings. The on-set temperature for the discontinuity in the HANA^{TM} claddings increased with an increase of Nb contents. The diffusivity of the HANA^{TM} claddings was measured, by using a laser flash method, in the temperature range from 25 to 1200^{o}C and increased monotonously with an increase of the measuring temperatures. The thermal conductivity was calculated from the product of the diffusivity, specific heat and density at a temperature. The thermal conductivities of the HANA^{TM} claddings were between 0.12 and 0.34 W/cm/K in the measuring temperature ranges and were almost similar to that of Zircaloy-4 cladding.

The surface emissivity of the HANA^{TM} claddings was measured at two temperatures of 400 and 1200^{o}C and was ranged from 0.37 to 0.83 regardless of the different composition. The emissivity of the HANA^{TM} claddings increased rapidly as the oxide thickness increased up to nearly 3.9 μm and was maintained a constant value in the case of the thicker oxide than 3.9 μm. These trends are well agreed with that of the reference Zircaloy-4 cladding. As already mentioned, the chemical composition of the HANA^{TM} claddings is different from that of Zircaloy-4. From this reason, the massive phase transformations of the HANA^{TM} claddings occurred at the temperatures of 770 to 808^{o}C, which were lower than that (~900^{o}C) of Zircaloy-4 cladding. The solidus temperatures of the HANA^{TM} claddings exhibited almost similar to that of Zircaloy-4.

The mechanical properties of Young's modulus and Poisson ratio were determined by the tensile and the internal burst tests for the HANA^{TM} claddings. Their Young's modulus was from 97.995 to 99.786 GPa at room temperature and their Poisson ratio was in the range of 0.370 to 0.372. The lattice and texture parameters of the HANA^{TM} claddings were obtained by a well-calibrated XRD. All measured lattice parameter of all HANA^{TM} claddings are almost same (a=3.2306 A, c=5.1493 A). The fraction of radial texture to (0002) pole was ranged from 0.63 to 0.67 for the HANA^{TM} claddings.

In shorts, the thermal and mechanical properties of the HANA^{TM} claddings were well characterized and were comparable to those of the reference Zircaloy-4 cladding. Based on these characterizing results, it is suggested that the HANA^{TM} claddings be prosperous for the commercial utilization in LWR plants.