Thermal and Mechanical Responses of ATF Cr-coated Zr-alloy Cladding under Multiple Water Quench Tests

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1. Introduction

Since the nuclear fuel vendors have been developing the Accident Tolerant Fuel (ATF) designs, licencing activities for the new fuels towards commercialization become important agenda. The examples includes evaluation of the ATF under various accident conditions such as loss-of-coolant accident (LOCA), reactivity initiated accident (RIA), and any transients in load-following scenario. During the LOCA, the regulation imposes that the fuel cladding should not be heated up to high temperatures (i.e., 1204 °C) since it induces significant mechanical degradation and hydrogen generation by the rapid oxidation of the Zr-alloy with high temperature steam. In LOCA, the Emergency Core Cooling System (ECCS) is activated, the cladding should be quenched through bottom reflooding. It is believed that the coated Zr-alloy cladding provides more reliable performance in the thermal trasient condition in terms of heat transfer response and post-quench ductility. This is because the excellent corrosion and oxidation resistance of the Cr coating. The previous work reported that the thermal response of the Cr-coated cladding in water quenching was comparable with that of uncoated cladding [1,2]. However, there was few information for the performance in repeated transients simulating accident conditions during load-following.

This study focuses on experimental investigation of thermal and mechanical response of Cr-coated cladding in water quenching using a single-rod reflood test facility. The quench tests were performed in a wide range of initial temperature and the tested samples were subjected to post-test characterization.

2. Methods and Results

2.1. Test Materials

The Zr-alloy cladding tubes used in the current work were ZIRLO®, provided by Westinghouse Electric Company (WEC). The full-length tubes were sectioned into 40 cm length individual samples to place into the test section in the quench test facility.

Cr coating for the Zr-alloy samples were conducted using cold spray deposition system at the University of Wisconsin, Madison (UW). The carrier gas was a mixture of He and N_2 to achieve high density coatings. The as-deposited coatings had ~75 µm thickness, which were then manually polished down to a uniform thickness of ~30 µm using SiC abrasive paper as shown in Fig. 1.

Fig. 1. Photographs of Zr-alloy tubes (Optimized Zirlo, OPZ) with Cr coatings with or without surface polishing. The coating was deposited using cold spray deposition technology.

The final surface finishing for the uncoated and Cr coated samples were 800-grit SiC abrasive papers to introduce the comparable surface conditions between the uncoated and coated tubes before testing.

2.2. Multiple Quench Tests

The water reflood quench test facility was constructed at UW to carry out reflooding experiments for the prepared samples. More details on the experimental facility design (Fig. 2) and test procedure can be found in somewhere else [3].

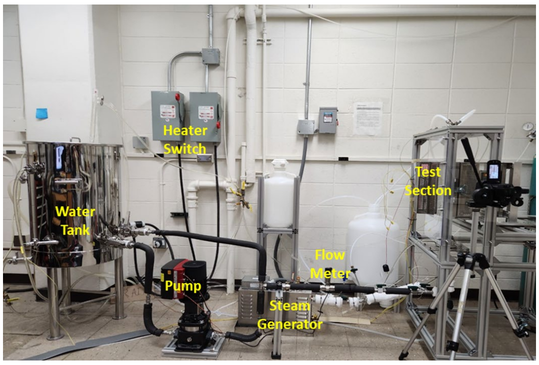

Fig. 2. Photograph of a single-rod water reflooding test facility at UW.

In this study, all quench tests were performed under 20 K water subcooling and a reflood velocity of 4.5 cm/s. The furnace temperature (i.e., initial sample temperature) was 800 °C or 1100 °C at a ramp rate of 10 °C/min. Inert gas was purged into the test section during the furnace heating to reduce undesirable oxidation of the cladding surface. Once the furnace temperature reached a target temperature, the hot water was supplied into the test section to introduce the bottom reflooding of the Zr-alloy cladding sample. The quench test is completed after the quench front was fully propagated and the activate boiling was completed along the sample.

For the multiple quench tests, the tested tube sample was subjected to additional quench tests until severe degradation of the sample surface was observed. In principle, the test was intended to provide cumulative oxidation of the sample while measuring the thermal behavior. In short, a total four sets of reflood tests were conducted: (1) single quench test at 800 °C or 1100 °C and (2) multiple quench test at 800 °C or 1100 °C. Finally, post-test visual inspection was conducted.

2.3. Quench Test Results

Rigorous inverse heat transfer analysis for quench curve data measured at the four different locations from the center of the sample (-60, -20, +20, +60 mm) determined the quench temperatures. Fig. 3 shows the quench temperatures of uncoated and Cr-coated samples at the initial temperature of 800 °C.

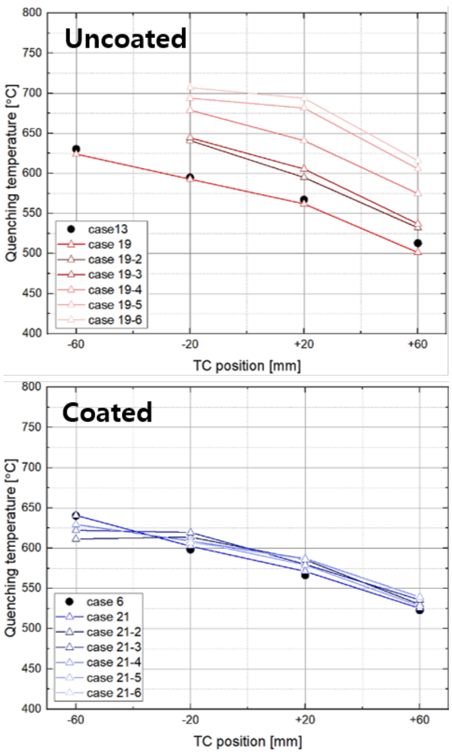

Fig. 3. Measured quench temperatures for uncoated and Cr-coated Zr-alloy at 800 °C initial temperature along with sample axial direction .

The triangle markers indicate quench temperature of the multiple test cases. For the single-quench tests (the solid markers), both uncoated and Cr-coated samples show similar quench temperatures and they decreases along with the axial location of the samples. Interestingly, the quench temperatures for the uncoated samples increase as the sample experienced the quenching multiple times. After six times quenching, the temperatures increased by about 100 °C compared to the single (or first) quench test. On the contrary, the quench temperatures for the coated samples showed the constant (no change) during the six times quenching. This is an indicative of minimal change of surface characteristics (e.g., oxide layer thickness) of the sample due to the Cr coating.

As shown in Fig. 4, the similar overall quench temperature trends were also confirmed even in the 1100 °C quench experiments. The quench temperatures for the uncoated sample showed significant scatter at this high temperature tests while the Cr-coated sample still exhibited consistent quench temperatures with the multiple quench tests.

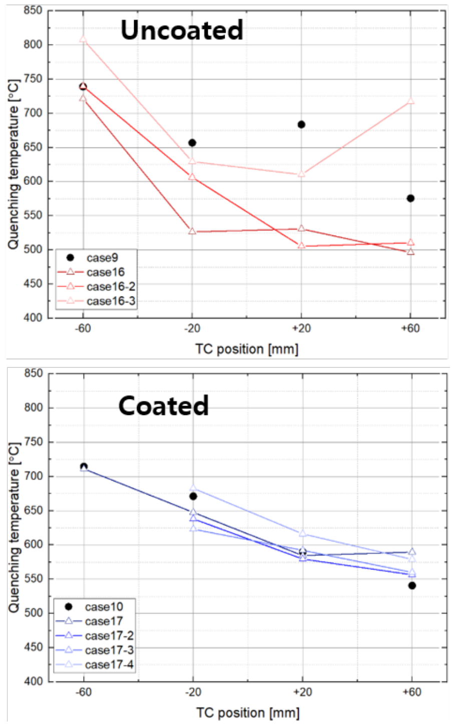

Fig. 4. Measured quench temperatures for uncoated and Cr-coated Zr-alloy at 1100 °C initial temperature.

2.4. Visual Inspection of Tested Samples

Fig. 5 shows photographs of the post-test samples (three times quench tests at initial temperature of 1100 °C). The uncoated sample broke easily when it was disassembled from the test section. Due to the severe oxidation, the surface looked black with circumferential white cracks. However, the coated samples only showed dark green color which is the typical color of Cr-oxide without showing any other surface defects. The post-test characterization of the samples using electro microscopy is in progress. This result demonstrates that the Cr-coating may provide improved mechanical integrity under a wide range of power transient conditions.

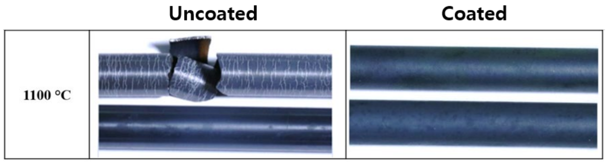

Fig. 5. Photographs of post-test samples (uncoated and Cr-coated) tested at 1100 °C initial temperature.

3. Conclusions

Cr-coated Zr-alloy cladding design is one of the most promising Accident Tolerant Fuel (ATF) cladding designs in light water reactor (LWR) on account of excellent corrosion and oxidation resistance under high temperature transient conditions. Multiple reflood experiments was performed for the coated cladding design to evaluate thermal behavior and mechanical integrity under potential severe thermal transient conditions. The experimental data was compared with uncoated cladding. The coated cladding exhibited highly repeated quench temperatures, heat transfer transition points in quench heat transfer. On the other hand, the uncoated cladding showed scattered quench temperature values as repeating the same tests at 1100 °C. Significant loss of mechanical durability of the uncoated samples was identified in the multiple quenching, although the coated samples under the sample condition remained intact. The results demonstrate that the coated cladding would provide improved integrity and performance under a wide range of power transient conditions in LWRs.

REFERENCES

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