A Comparative Study of the Mechanical Test Metrics for Fuel Cladding after Simulated LOCA Test

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1. Introduction

Ballooning and rupture phenomenon of fuel cladding during loss-of-coolant accident(LOCA) scenarios occurs due to pressure difference between inner and outer cladding at high temperature. These phenomena have a significant impact on the integrity of nuclear fuel. Ballooning may cause the fuel relocation and fuel dispersal can occur due to its rupture opening during accidents. However, a current LOCA criterion is based on the results obtained from non-pressurized and relatively short claddings specimens under simulated LOCA condition. In addition, effects of mechanical constraints or axial load can be applied during quench were neglected. In this study, the mechanical properties of ballooned and ruptured cladding were evaluated and compared with ring compression test results. Its applicability to existing LOCA criteria was also investigated and discussed.

2. Methods and Results

In this section some of the experimental procedure and technical details of apparatus are described. Highlight data obtained from axial tensile test of ballooned and ruptured cladding sample is also presented.

2.1 Integral LOCA Test

For the integral LOCA tests, 400 mm long tubular zir caloy-4 cladding samples were filled with 10 mm long alumina pellets to simulate the heat capacity of the fuel. The furnace was heated to a pre-test hold temperature of 300℃ within 240 s, where the steam flow and sample temperature were stabilized for 500 s. A heating rate of 5℃/s from 300℃ to 1200℃ was used. After exposure for a time corresponding to 13 to 20% of equivalent cladding reacted (ECR) at 1200℃, the tube was cooled slowly to 800℃ and then quenched by flooding from the bottom of the chamber with water. Further details of the test equipment and experimental procedures can be found in our previous paper [1].

2.2 Axial Tensile Test

After quenching, cooling water was drained and tensile test was carried out by pulling the specimen the specimen from the bottom. Axial tensile test can be performed at seven different rates, as shown in Fig. 1. In this study, the cladding specimens were stretched at a speed equivalent to RPM1 (tensile speed about 10N/s). JAEA argued that axial restraint loads had to be less than 1,000 N. It adopted 540 N for its partially restrained tests using irradiated cladding samples [2, 3]. All the tensile tests were conducted with maximum loads of 500N.

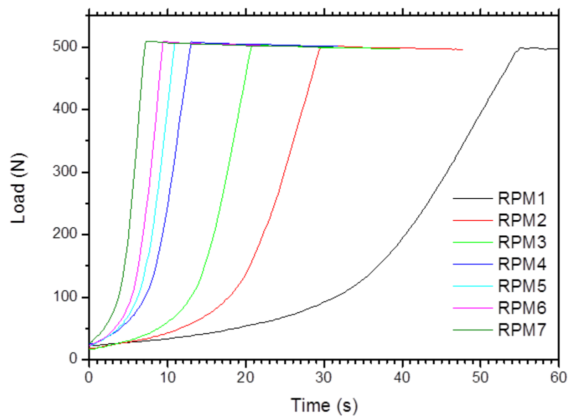

Fig. 1. Load obtained tensile test performed at room temperature with different RPM of motor.

2.2 Ring Compression Test

After oxidation, the tube was cooled slowly and quenched at ≈800°C by bottom flooding. Several short ring specimens having a 8 mm length were cut from the tube for the testing of post-quench ductility. Slow ring-compression tests were performed at 135℃ at a compression rate of 0.033 mm/s.

Metallography was performed for zircaloy-4 samples oxidized up to 393 s. This oxidation time correspond to a CP-ECR value of 20%. The results for these times are shown in fig. 2 at low magnification. Zircaloy-4 cladding clearly shows the oxide layers increasing with the exposure time.

Tensile test results obtained those samples were shown in Fig. 3. Under maximum load of 500N, all samples with 13, 15, and 17 %ECR were survived without failure after axial tensile test. However, ballooned and ruptured sample with 19% ECR was failed under a load of less than 500N. Ring compression tests for 8 mm long ring sample cut from oxidized Zircaloy-4 cladding were conducted and shown in Fig. 4.

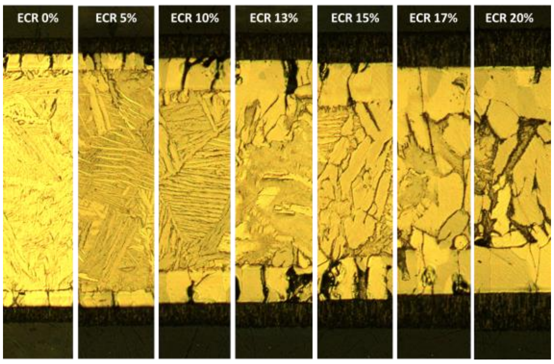

Fig. 2. Low magnification of inner- and outer-surface oxide layers for zircaloy-4 cladding oxidized at 1200C with different oxidation time.

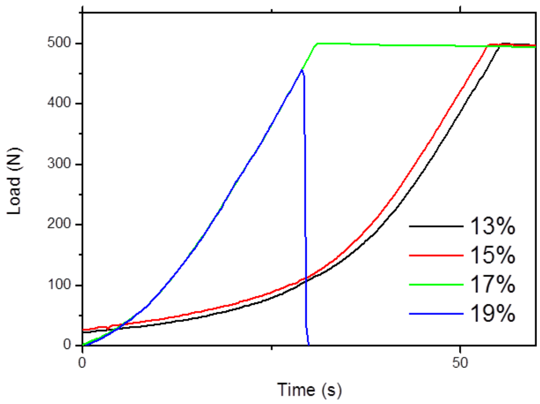

Fig. 3. Load as a function of time obtained tensile test for cladding samples with different ECR.

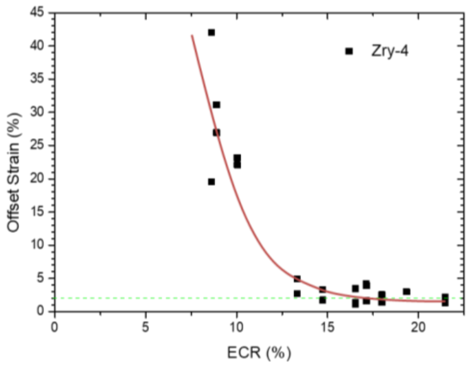

Fig. 4. Offset strain measured after ring compression test for cladding samples with different ECR.

It is noteworthy that the abrupt change of mechanical property is similar to the existing criteria based on the ring compression test. However, it is necessary to confirm it through more repeated tests. That is, the research program was not extensive enough to develop any alternate metric, and pursuing an alternate metric, particularly for the ballooned and ruptured region of a fuel rod, is not recommended at this time.

3. Conclusions

Two test metrics to develop the embrittlement limits for cladding samples after LOCA tests. It is found that similar abrupt change of mechanical property was observed, despite of different test metrics. However, this research program was not extensive enough to develop any alternate metric. Tests on Zr-4 with different controlled load rates and balloon shapes are planned to confirm their dependency of the fracture load

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