Transactions of the Korean Nuclear Society Autumn Meeting
Yeosu, Korea, October 25-26, 2018

Burst Opening Area of HANA-6 Cladding in Simulated LOCA Conditions

H. Jang*, S. Y. Lee, Y. H. Kim, J. I. Kim, Y. K. Mok
KEPCO Nuclear Fuel, R&D Center, 242, Daeduk-daero 989beon-gil, Yuseong-gu, Daejeon, 34057,Korea
**Corresponding author: janghoon@knfc.co.kr*

1. Introduction

HANA-6 alloy has been developed for application of nuclear fuel cladding material. Several lead test rod (LTR) and lead test assembly (LTA) programs have been successfully conducted in commercial reactors. Superior properties of HANA-6 cladding were verified from pool-side examination (PSE) after LTR and LTA programs. Also, to verify the superior properties of HANA-6 cladding up to higher burn-up, an additional LTR program of HANA-6 cladding is being irradiated up to 65 GWD/MTU. The post-irradiated examination (PIE) programs of HANA-6 cladding irradiated in commercial reactors are planned.

Recently, the fuel fragmentation, relocation, and dispersal (FFRD) during LOCA situation has been emerged as one of the critical obstacles for licensed burn-up extension of nuclear fuel [1,2]. Based on recent research results [1,2], FFRD is affected by fuel average burn-up as well as cladding burst behaviors such as burst strain, depressurization of internal rod pressure when cladding is burst, and burst opening area. Among these systematic parameters, the burst opening area could determine the critical fragmentation size for dispersal. Furthermore, it is possible that the burst opening area could be affected by test conditions such as heating rate, internal rod pressure, and cladding properties. In this regards, the burst opening behaviors of HANA-6 cladding is very important to evaluate FFRD. KEPCO NF has performed a lot of burst tests of HANA-6 cladding in simulated LOCA conditions to burst model development. In this study, the burst opening areas of HANA-6 with various test conditions were measured from tested specimens and well characterized.

2. Experimentals

The cladding burst tests were conducted by using LOCA burst test system that was described in previous paper [3]. The length of tube specimens was 300 mm and the specimens prepared by welding 3 thermocouples (TCs) at longitudinally 120 mm, 160 mm, and 200 mm from the top of tube specimen with azimuthally 120° intervals. The temperature of burst location of specimen was calculated by linear interpolation between two TC readings that spot-welded at below and above the burst location. To simulate the pellet inside of tube, alumina pellets were inserted inside of the specimens before the tests.

The tests were performed in flowing steam/Ar mixed environment. The heating rates were controlled to 1, 2.5, 5, 14, 28, and 50 °C/s. The internal pressure of cladding was controlled by pressurized He gas at which target engineering hoop stress of cladding was achieved in the range of 7 ~ 100 MPa. Internal pressurized cladding specimens were stabilized at 300 °C steam environment for 5 min. And, the specimens were heated at desired heating rate until the specimen is ruptured. The procedure for cladding burst test was shown in Fig. 1.

After the tests, the maximum circumferential burst strain at the burst location of the ruptured cladding specimen was measured by non-elongated tapes and a calibrated micrometer. The burst opening area of test specimens were directly measured by using area measuring device (Wacom PTH-651) and Inspector matrox imaging software.

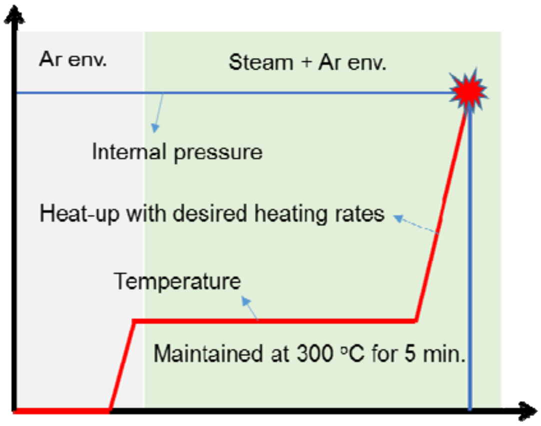


Fig. 1. Procedure for cladding burst tests.

3. Results and Discussion

Figure 2 shows the burst strain of HANA-6 as a function of burst temperature. The lower burst strain region (called as valley) was observed in temperature region between 800 °C and 900 °C that was well corresponded to the phase transformation temperature of HANA-6 ($\alpha+\beta$: 740 ~ 960 °C). In addition, the burst strain of HANA-6 cladding was increased with decreasing heating rate in whole tested temperature range.

Figure 3 shows the axial diameter profile of HANA-6 cladding tested at various heating rates and two engineering hoop stresses (20 MPa and 60 MPa). It is clearly shown that the largest diameter at the burst center and it was gradually increased with decreasing heating rate. Besides, the pre-rupture strain away from burst center was larger at lower heating rate. It is thought that the large creep deformation at slower heating rate could increase the pre-rupture strain because the time to creep deformation during heat-up phase could be longer at slower heating rate. As a consequence, it is thought that the large pre-rupture strain could induce the larger burst strain at slower heating rate.

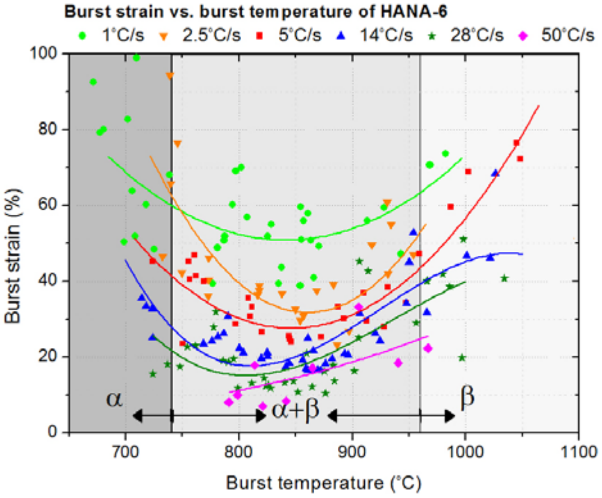
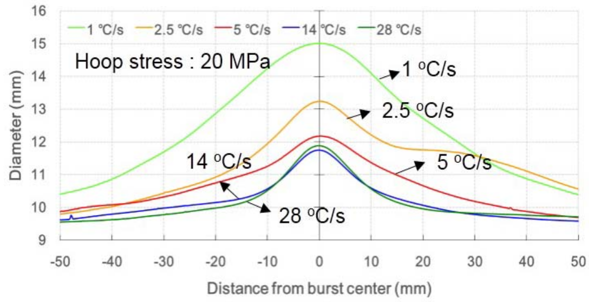
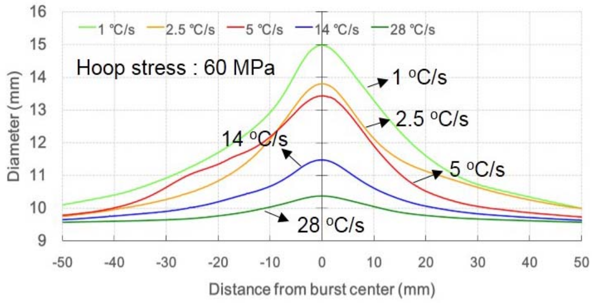


Fig. 2. Burst strain vs. burst temperature at various heating rates.



(a) 20 MPa



(b) 60 MPa

Fig. 3. Axial diametral profile of the ruptured tube at engineering hoop stress of; (a) 20 MPa, (b) 60 MPa.

Figure 4 shows the burst temperature as a function of engineering hoop stress of HANA-6 cladding. The burst temperature of HANA-6 cladding was increased with increasing heating rate up to 14 °C/s. The higher burst temperature at faster heating rate might be related to the larger pre-rupture strain at slower heating rate as shown in Fig. 3. It could be simply thought that the thinning of cladding thickness with increase of pre-rupture strain could increase the true-hoop stress applied in cladding. Thus, the burst temperature could be decreased at slower heating rate. However, the burst temperature at the heating rate of 28 °C/s were similar with those tested at the heating rate of 14 °C/s although the pre-rupture strain at the heating rate of 14 °C/s was slightly larger than those at the heating rate of 28 °C/s. It is thought that the data scatter hid the small amount of difference of pre-rupture strain between test data at 14 °C/s and 28 °C/s.

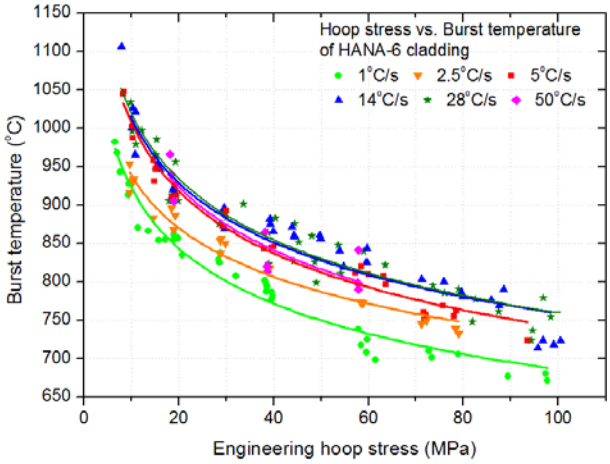


Fig. 4. Burst strain vs. burst temperature at various heating rates.

Figure 5 shows the burst opening area as a function of burst temperature of HANA-6 cladding. The burst opening area were decreased with increasing burst temperature up to 850 °C. But, those were not changed at the burst temperature above 850 °C. This tendency was very well corresponded with NUREG-0344 data [4] and model that was based on Zry-4 cladding. Compared with the test results of the burst strain according to burst temperature as shown in Fig. 2, it was observed that the burst opening area were increased with increase of burst strain at below 850 °C. It could be inferred that the larger burst opening area with the larger burst strain was due to cladding thinning with larger burst strain and high hoop stress. On the other hand, the burst opening area were not varied with burst strain above 850 °C. In higher temperature in steam environment, the oxidation induced embrittlement of cladding might be responsible for the reduction of burst opening area despite of larger burst strain.

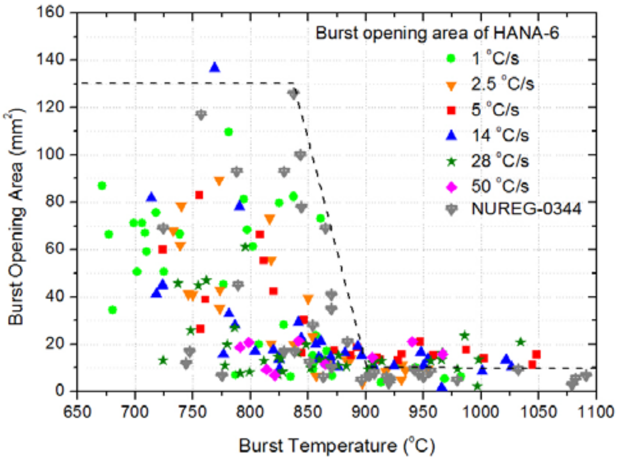


Fig. 5. Burst opening area of HANA-6 as a function of burst temperature.

Figure 6 shows the burst opening area according to engineering hoop stress. Despite of large data scatter, it was observed that the burst opening area was affected by heating rates. In overall, the burst opening area was increased when the applied hoop stress reaches the certain threshold hoop stress. And, those were saturated at which the burst opening area is about 60 mm^2. The threshold hoop stress were depended on the heating rate. At the lower heating rate, the threshold hoop stress was decreased. This effect of heating rate on threshold hoop stress for increase in burst opening area will be discussed based on a lot of burst database.

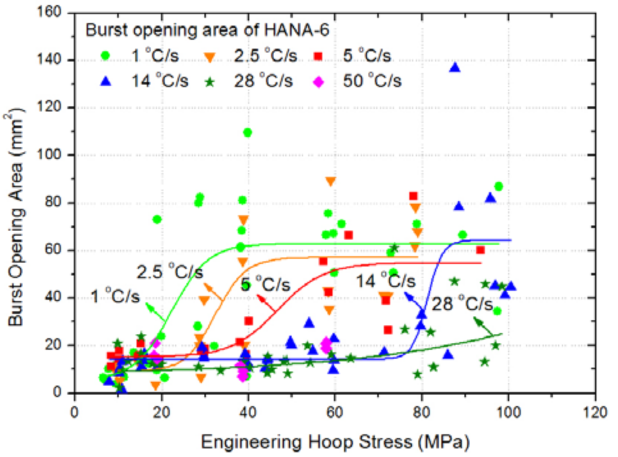


Fig. 6. Burst opening area of HANA-6 as a function of the engineering hoop stress.

3. Conclusions

A lot of burst tests of HANA-6 tubes were performed at various heating rates and engineering hoop stresses. The experimental observations were summarized as bellows.

1. The burst strain as a function of burst temperature was decreased with increasing heating rate at whole burst temperature range.
2. The burst temperature as a function of engineering hoop stress was increased with increasing heating rate from 1 ºC/s to 14 ºC/s. but, the effect of heating rate on burst temperature were not observed at above 14 ºC/s.
3. Below burst temperature of 850 ºC, The burst opening area was decreased with increasing burst temperature. But, above 850 ºC, the burst opening area was not varied with burst temperature
4. The burst opening area was increased when the applied hoop stress reaches the certain threshold hoop stress. The threshold hoop stress was depended on heating rate.

REFERENCES

[1] NEA WGFS, “NEA/CSNI/R(2016)16: Report on Fuel Fragmentation, Relocation and Dispersal”, 2016.

[2] P. A. C. Raynaud, “NUREG-2121: Fuel Fragmentation, Relocation, and Dispersal During the Loss-of-Coolant Accident”, US NRC, 2012.

[3] H. Jang, S. Y. Lee, D. I. Kim, J. Y. Lim, Y. H. Kim, Y. K. Mok, Experimental Observation on Burst Behaviors of HANA-6 Cladding in LOCA Conditions, Transactions of the Korean Nuclear Society Autumn Meeting, May 18-10, Jeju, Rep. of Korea.

[4] H. M. Chung, T. F. Kassner, “NUREG-0344 : Deformation Characteristics of Zircaloy Cladding in Vacuum and Steam under Transient-Heating Conditions, US NRC, 1978.