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Experimental Observation on Burst Behaviors of HANA-6 Cladding in LOCA Conditions

Hun Jang*, Sung Yong Lee, Dae Il Kim, Jea Young Lim, Yoon Ho Kim, Yong Kyoon Mok
Department of Nuclear Fuel Technology, KEPCO NF, 242, Daedeok-daero, 989beon-gil, Yuseong-gu, Daejeon
**Corresponding author: janghoon@knfc.co.kr*

1. Introduction

HANA (High performance alloy for nuclear application) alloy was developed in order to meet the global demand for an extension of the fuel discharge burn-up to more than 70 GWd/MtU. Several lead test rod (LTR) and lead test assembly (LTA) programs have been successfully conducted in commercial reactors [1]. Superior properties of HANA-6 cladding were verified from pool-side examination (PSE) after LTR and LTA programs [1, 2]. Also, post-irradiated examination (PIE) of HANA-6 cladding irradiated in commercial reactors is being conducted. Besides, the performance of HANA-6 cladding in loss of coolant accident (LOCA) conditions should be evaluated. Since it is known that cladding burst behaviors could induce the coolant blockage during LOCA, the understanding on burst behaviors of HANA-6 cladding and the related burst model are necessary to analyze the nuclear fuel behaviors during LOCA.

In this study, many of burst tests of HANA-6 cladding in simulated LOCA conditions have been performed. The experimental observation from the burst tests were summarized.

2. Experimentals

A special set-up was developed and qualified to conduct the cladding burst tests in simulated LOCA condition as shown in Fig. 1. The test system was designed with 6 infra-red (IR) heaters, steam generator, pressurizing system in inside of tube. The maximum temperature of test system is about 1200 ^{o}C with maximum controllable heating rate of 50 ^{o}C. The inner pressure of tube specimen was designed up to 130 bar. All of detecting and control devices were calibrated from qualified organizations by KOLAS.

Fig. 1. LOCA burst test system.

For qualification of test system, axial and circumferential temperature variations were confirmed in range of 80 mm in total 300 mm of cladding specimen. The three K-type thermocouples (TC) were circumferentially welded with 120 degree intervals. It was confirmed that the azimuthal temperature difference were maintained below ± 10 ^{o}C. In addition, three thermocouples were longitudinally welded at 120 mm, 160 mm, and 200 mm from the top of tube specimens. The temperature variations along axial direction were ± 20 ^{o}C. The temperature at the burst region could be obtained by linear interpolation between two TC readings. The heating rates were controlled to 5, 14, and 28 ^{o}C/s. The internal pressure of tube was controlled by pressurized He gas at which target engineering hoop stress of tube was achieved in the range of 7 ~ 100 MPa. A temperature and pressure curves from a representative burst test are shown in Fig. 2.

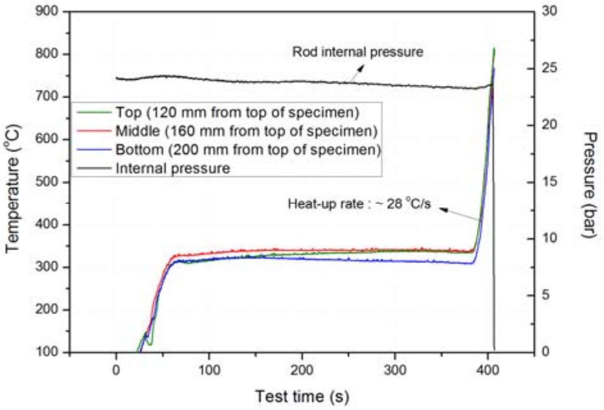

Fig. 2. Temperature and internal rod pressure curve during a representative burst test of HANA-6.

2. Results and Discussion

Figure 3 shows relationship between hoop stress and burst temperatures of HANA-6 cladding. The test results were compared with NUREG-0630 model which was based on experimental data of Zircaloy-4 [3]. The burst temperatures of HANA-6 cladding with increasing hoop stress showed similar tendency with NUREG-0630 model [3]. However, the burst temperatures of HANA-6 cladding were not dependent on heating rates. The reason why this independence of burst temperature on heating rate has not been founded in this study.

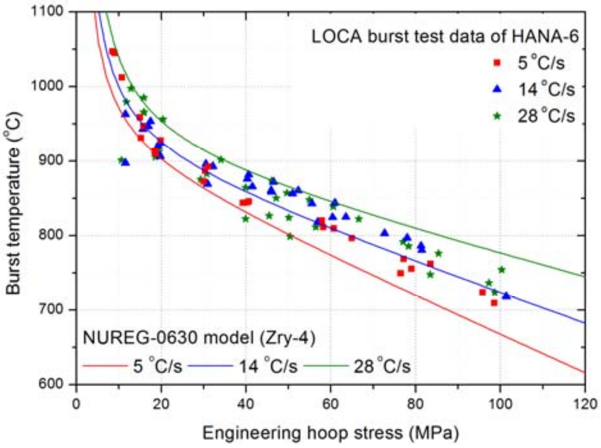

Fig. 3. Engineering hoop stress vs. burst temperature.

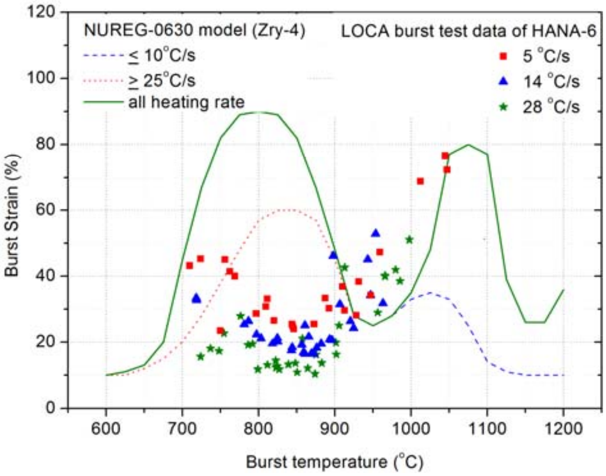

Fig. 4. LOCA burst test result of HANA-6 cladding.

Figure 4 shows the relationship between burst temperatures and burst strains. As shown in the figure, the lowest burst strain of HANA-6 cladding were observed in temperature range from 800 to 900 °C, which are different from NUREG-0630 model [3]. It has been known that the ductility drop in these temperature range is due to the low ductility of the mixed phase of alpha and beta. Therefore, the ductility drop in the lower temperature range when compared with NUREG-0630 model is due to lower phase transition temperature of HANA-6 ($\alpha+\beta$:740 ~ 960 °C) than Zircaloy-4 ($\alpha+\beta$: 820 ~ 975 °C). In addition, the burst strains of HANA-6 were increased with decreasing heating rates at temperature range of 700 ~ 900 °C. At these temperature range, the tube specimens at lower heating rates could have more time for deformation. It was consistent with burst model of Zircaloy-4 from NUREG-0630 which were lower burst strains at higher heating rates. However, in higher burst temperature range at applied lower hoop stress, the burst strains were not varied with heating rates. It is thought that oxidation induced embrittlement at high temperature could decrease the burst strains at lower heating rates.

3. Conclusions

Much of burst tests of HANA-6 tube were performed at various heating rates and engineering hoop stress. The experimental observation were summarized as bellows.

1. From the hoop stress vs. burst temperatures curves, the burst temperatures were not depended on the heating rates.
2. From the burst temperatures and burst strain curve, the lowest burst strain region were observed at the temperature range from 800 °C to 900 °C.
3. In the range of lower burst temperature below 900 °C, the burst strain was increased with decreasing heating rate. On the other hand, above 900 °C, the burst strain was not affected by heating rates.

Acknowledgements

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