Hydride Effect on the Tensile Properties of HANA-4 Alloy

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1. Introduction

KAERI has developed some Zr-based new alloys, called HANA alloys, for high burn-up fuel cladding material. The sample specimens of HANA cladding tube material showed good performance in corrosion and creep properties at the irradiation test in Halden test reactor up to 10GW/MtU as well as the un-irradiation tests. Zirconium alloys has been used as nuclear fuel cladding material because they have satisfactory mechanical strength and corrosion resistance. It was reported that zirconium alloys responded abnormally in mechanical behavior over a certain temperature and strain rates [1-4]. For example, the embrittlement of Zircaloy-4 (Zr-1.5Sn-0.2Fe-0.1Cr) alloy can be increased over 227 ~ 427℃ due to dynamic strain aging(DSA). The change of mechanical properties of HANA-4(Zr-1.5Nb-0.4Sn-0.2Fe-0.1Cr) alloy from DSA was already studied from room temperature to 500℃ when its specimens had been tested with the strain rate of $1.67x10^{-2}$/s and $8.33x10^{-5}$/s [4].

When a zirconium alloy is used in a nuclear reactor, hydrides form in it from not only external hydrogen sources such as waterside corrosion, dissolved hydrogen in coolant, water radiolysis but also internal sources such as hydrogen content in fuel pellets and moisture absorbed by the uranium dioxide fuel pellet [5]. Hydrogen embrittlement of zirconium alloys has been extensively studied because hydrides may act as a sudden failure at very low strain [6]. For low and medium hydrogen content, the hydrides crack during tensile loading and accelerate the ductile fracture process [7]. To study the effect of hydride on the mechanical properties of HANA-4 cladding tube which had been finally heat-treated at 470℃, this research was done with tensile tests as an extension of the prior study [4].

2. Methods and Results

The cladding tube specimens of HANA-4 alloy with 150mm in length were charged with 500ppm by a hydrogen gas charging. After being hydrided, the specimens were heat-treated for 30 minutes at 410℃ in order to homogenize the hydrogen content in the specimens. It was found by gas analysis that actual hydrogen content of the specimens was 526.2 ppm. The test specimens were cut from the hydrogen charged specimens and machined by electron discharge as the semi-tube tensile specimens with the dimension of 4mm in the reduced width, 20mm in the length of gage section and 60mm in total length. The tensile tests of specimens were carried out in 10^{-2} torr environment from room temperature to 500℃ with the strain rate 10^{-2}/s, 10^{-3}/s and 10^{-4}/s.

2.1 Effect of Test Temperature and Strain Rate

Fig. 1 shows the yield stress of non-hydrided HANA-4 cladding specimens and Fig.2 shows that of 500 ppm hydrided ones at different temperature and different strain rate. The main factor of DSA is the interaction of solute atoms, precipitates and the other defects or impurities in alloys with moving dislocations. Oxygen atoms are responsible for the DSA of Zircaloy-4 fuel cladding tube which appears between 300~400℃ [1]. If the solute atoms in an alloy, such as oxygen, hydrogen, are properly activated by heat, they would be captured by the moving dislocations when the alloy is deformed with appropriate strain rate. Thus, more drag force is added to the dislocation moving force and a hump would appear on the flow stress-temperature diagram. As seen Fig. 1, the non-hydrided specimens showed a light hump at 350℃ when they were deformed with the strain rate of 10^{-4}/s. But when they did deform with the faster strain rate, it did not appear. The moving dislocations might be faster than solute atoms which could be captured.

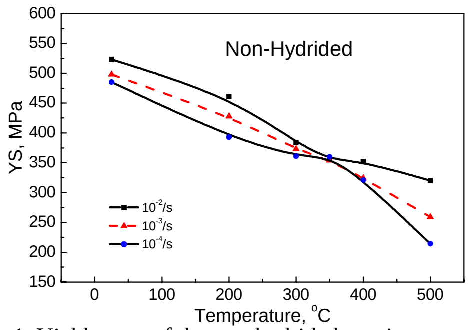

Fig. 1. Yield stress of the non-hydrided specimens

The hydrogen solubility of Zr-based alloys is about 10ppm to 110 ppm in the range of 200 ~ 400℃ in which they indicate DSA effect [8]. Fig. 2 shows that 500 ppm hydrided specimens have a hump more remarkably on the diagram than non-hydrided ones. The hydrogen content over solubility limit would contribute to the notable DSA effect.

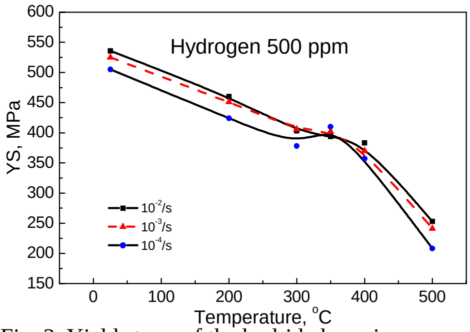

Fig. 2. Yield stress of the hydrided specimens

2.2 Fracture Surfaces of the Specimens

Fig. 3 shows the fracture surfaces of both non-hydrided and 500ppm hydrided specimens when they had tensile test at 25, 350, and 500°C with the strain rate of 10^{-4}/s. With the remarkable DSA phenomenon, the dimple sizes on the facture surfaces at 350°C are smaller than those at the other temperature. The dimple size and depth of the fracture surfaces of 500ppm hydrided specimens are smaller and shallower that those of non-hydrided ones. Especially, the hydrogen atoms over the solubility limit would be precipitated into hydrides, which caused brittle fracture at 25°C.

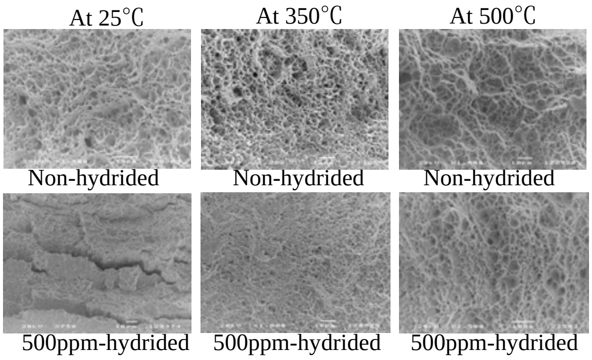

Fig. 3. Fractographs of both non-hydrided and 500ppm hydrided specimens (x1000)

3. Conclusion

To study the effect of hydride on the mechanical properties of HANA-4 cladding tube which had been finally heat-treated at 470°C, The tensile tests of both non-hydrided and 500ppm hydrided specimens were carried out in 10^{-2} torr environment from room temperature to 500°C with the strain rate 10^{-2}/s, 10^{-3}/s and 10^{-4}/s.

The both specimens showed a DSA effect around 350°C. Especially, 500 ppm hydrided specimens showed more remarkable DSA effect than that of non-hydrided ones. So, it appears that hydrogen can contribute to the DSA effect of the HANA-4 cladding tube. At room temperature, the hydrogen over solubility limit would precipitate into hydrides which could lead brittle fracture.

Acknowledgement

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REFERENCES

[1] Ki Seong Park and Byong-Whi Lee, J. KNS, Vol.21(2), June, 1989

[2] Jae-Kyung Yi, Heung-Bae Park, Gi-Sung Park and Byong-Whi Lee, J. Nucl. Mater. Vol. 189, p. 353, 1992

[3] Soon Kil Kim, Hyoung Seop Kim, Sun Ig Hong, Chang Burn Choi, Kyu Tae Kim, J. Kor. Inst. Met.& Mater. Vol. 37(12), p. 1482, 1999

[4] M.H. Lee, J.H. Kim, B. K. Choi and Y.H. Jeong, Kor. J. of Mater. Res. Vol. 14(10), p. 713, 2004

[5] S.I. Hong, K.W. Lee, JNM Vol. 340, p. 203, 2005

[6] J.H. Huang and S.P. Huang, JNM Vol. 208, p. 166, 1994

[7] J.B. Bai, C. Prioul and D. Francois, Metal.&Mater. Trans. A Vol. 25A, p. 1185, 1994

[8] D. Khatamian, J. Alloys & Compounds, 293-295, p. 893, 1999