ELSEVIER
Journal of Alloys and Compounds 330–332 (2002) 404–407
Journal of ALLOYS AND COMPOUNDS
www.elsevier.com/locate/jallcom

Tensile test of hydrided Zircaloy

Masatoshi Kuroda[a,*], Shinsuke Yamanaka[a], Daigo Setoyama[a], Masayoshi Uno[a], Kiyoko Takeda[b], Hiroyuki Anada[b], Fumihisa Nagase[c], Hiroshi Uetsuka[c]

[a]*Department of Nuclear Engineering, Graduate School of Engineering, Osaka University, Yamadaoka 2-1, Suita, Osaka 565-0871, Japan*
[b]*Sumitomo Metal Industries Ltd., Fuso-cho, Amagasaki, Hyogo-ken 660-0891, Japan*
[c]*Department of Reactor Safety Research, Japan Atomic Energy Research Institute, Tokai-mura, Ibaraki-ken 319-1195, Japan*

Abstract

In order to examine the influence of precipitated zirconium hydride on the failure behavior and fracture strength of light water reactor (LWR) cladding tubes, tensile tests were performed at room temperature for non-hydrided and hydrided Zircaloy sheet-type specimens with gauge section of 10.0×5.0 mm and thicknesses of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 mm. For specimens with thickness more than 2.5 mm, the ultimate tensile strength of the specimens appeared to be independent of thickness, which implied that plane strain condition was attained. For the specimen with 2.5 mm thickness, the ultimate tensile strength increased slightly with increasing average hydrogen concentration. Through microscopic observation of the hydrided specimen surface by scanning electron microscopy (SEM), it was found that matrix/hydride debonding was not generated but that micro-cracks perpendicular to the axial direction were produced at the hydride layer.

Keywords: Zircaloy; Zirconium hydride; Hydrogen embrittlement; Fracture strength; Tensile test

1. Introduction

In order to maintain structural integrity of the high burn up fuel rods, the fracture behavior during reactivity initiated accidents (RIAs) as well as normal operating conditions has to be studied. In the Nuclear Safety Research Reactor (NSRR) of the Japan Atomic Energy Research Institute (JAERI), a series of experiments using pulse irradiation facilities has been performed to study the high burn up fuel behavior under RIA conditions [1]. The results of the NSRR showed that the cladding failures were strongly influenced by the pre-existing hydride. The failure originated from pellet-clad mechanical interaction (PCMI) accompanied by hydrogen embrittlement. In order to simulate the PCMI which occurs during the pulse irradiation in the NSRR, high-pressurization-rate burst tests have been performed in the JAERI by applying pressure from the inside of the cladding tubes with hydraulic power [2,3]. The fracture behavior and the burst pressure of the hydrided cladding in the burst test have already been well analyzed by the present authors [4,5] using finite element method (FEM) and fracture mechanics. However, it appears that burst tests are unsuitable for a systematic study of the fracture strength and the fracture mechanism because of complicated stress states in the cladding and difficulties in the observation of the fracture behavior. Therefore, tensile tests for simple models such as sheet-type specimens will be effective. There have been several reports of tensile tests for hydrided zirconium alloys [6–11]. Choubey et al. [8] have noted that the fracture mode of the specimen depends on the specimen thickness, which is due to stress states in the specimen. In general, plane strain condition exists in thick bodies, while plane stress in thin ones [12]. Mechanical properties under plane strain, for example, plane strain fracture toughness (K_{IC}), are essential parameter for failure assessment because of independent of specimen thickness. In the present study, tensile tests were carried out for Zircaloy sheet-type specimens with different thickness to estimate the fracture strength under plane strain condition. The hydrided specimen surface was observed through scanning electron microscopy (SEM), and fracture mechanisms of the specimens were studied.

2. Experimental

The material employed was hot-rolled Zircaloy-4 plate with initial dimensions of 20×100×120 mm (H×W×L).

*Corresponding author. Tel.: +81-6-6879-7905; fax: +81-6-6879-7889.
E-mail address: mkuroda@nucl.eng.osaka-u.ac.jp (M. Kuroda).

0925-8388/02/$ – see front matter
PII: S0925-8388(01)01493-1

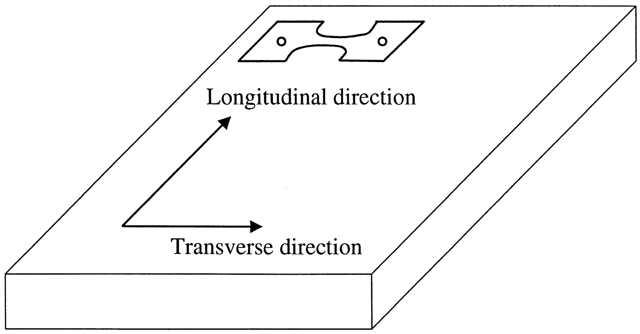

Fig. 1. Diagram showing the orientation of the tensile specimen cut out from Zircaloy-4 plate.

The plate was cold-rolled in the longitudinal direction to approximately 15×100×160 mm (H×W×L), and then in the transverse direction to approximately 10×130×160 mm (H×W×L). After vacuum-annealing at 480°C for 2 h, sheet-type tensile specimens with having gauge section of 10.0×5.0 mm and thicknesses of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 mm were cut from the plate such that the tensile axis was in the transverse direction of the plate as shown in Fig. 1. Some of the specimens were hydrogenated at 400°C to the nominal levels of 300–900 ppm H, which was estimated by weight gain. The hydrided specimen had the δ-phase of zirconium hydride platelets distributed uniformly and oriented parallel to the tensile axis. Tensile tests were carried out for the non-hydrided and hydrided sheet-type specimen at room temperature at a strain rate of 3.3×10^{-4} s^{-1} to monitor the stress–stroke relation by PC.

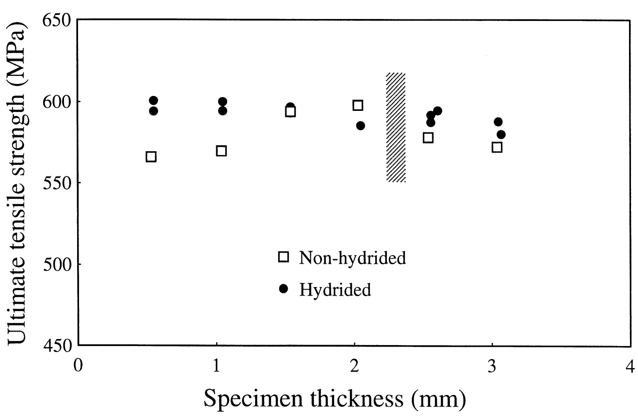

Fig. 2. Effect of specimen thickness on the ultimate tensile strength for the non-hydrided and hydrided specimens.

3. Results and discussion

3.1. Tensile properties

Fig. 2 shows the ultimate tensile strength of the non-hydrided and hydrided specimens as a function of the specimen thickness. For the specimens with the thickness of more than 2.5 mm, the ultimate tensile strength of both the non-hydrided and hydrided specimens appears to be independent of specimen thickness. Figs. 3 and 4 indicate the fracture morphology of the non-hydrided and hydrided specimens, respectively. As shown in these photographs, significant change was observed in the fracture modes from slant fracture to fully flat fracture with increasing specimen thickness. The flat fractures as shown in Fig. 3b and Fig. 4b tend to occur at the plates where plane strain condition of deformation exists [13]. Consequently, plane strain condition was assumed for the specimen with more than 2.5 mm thickness.

The stress–stroke diagram of the non-hydrided and hydrided specimens with 2.5 mm thickness is shown in Fig. 5. This diagram indicates that significant degradation of the ductility and increase in the ultimate tensile strength

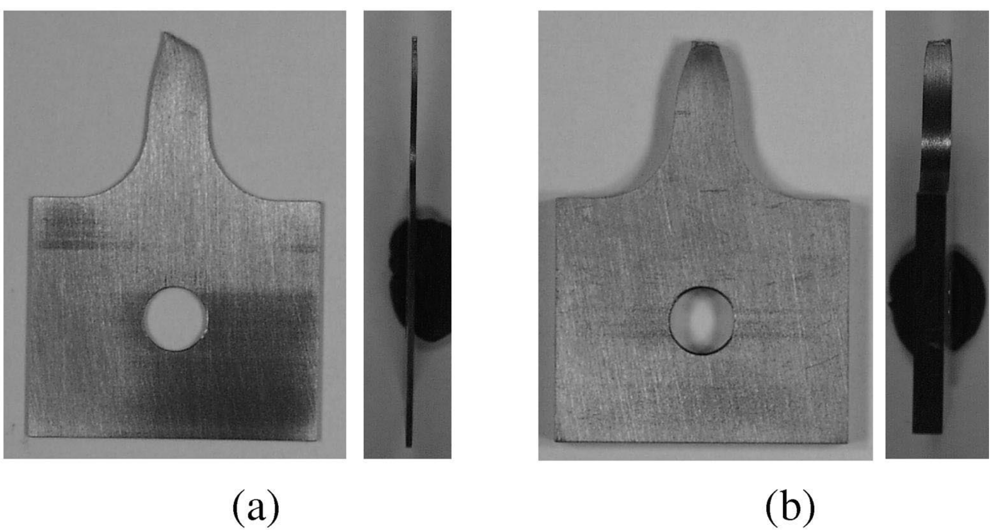

Fig. 3. Tensile fractures of the non-hydrided specimens with thicknesses of (a) 0.5 mm and (b) 2.5 mm.

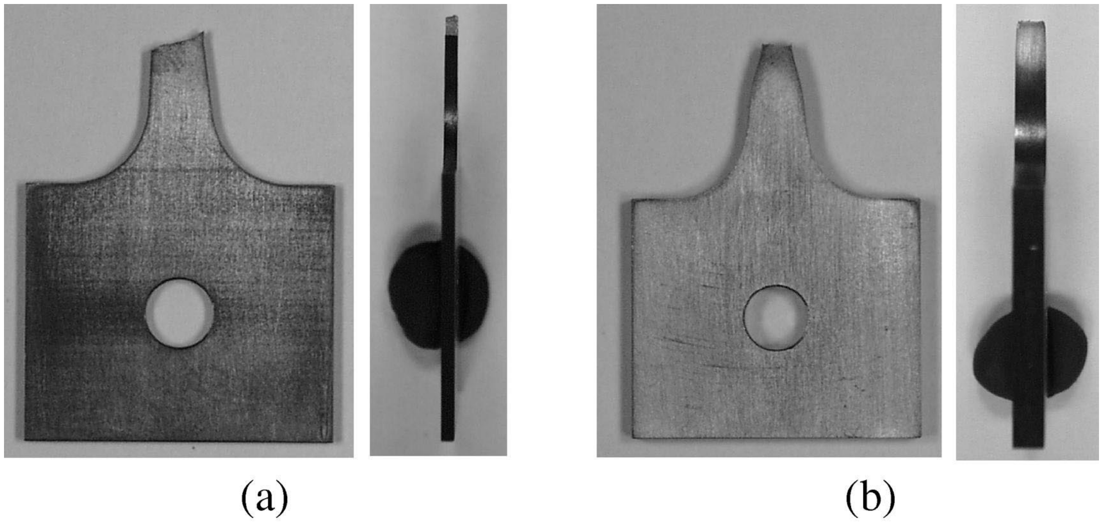

Fig. 4. Tensile fractures of the hydrided specimens: (a) 1.0 mm thickness specimen with hydrogen concentration of 722 ppm, and (b) 2.5 mm thickness specimen with hydrogen concentration of 543 ppm.

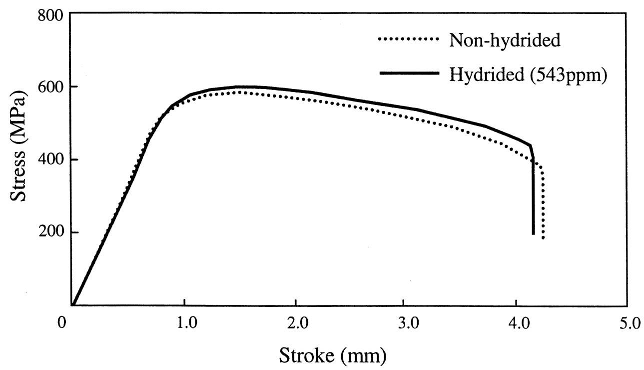

Fig. 5. The stress–stroke diagram for the specimens with 2.5 mm thickness.

were not observed, although hydride existed. Therefore, the hydrided specimen with the hydride platelets oriented to the axial direction is considered to be less sensitive to hydrogen embrittlement. Fig. 6 reveals the effect of the average hydrogen concentration on the ultimate tensile strength for the 2.5-mm thick specimen where plane strain fracture occurred. It is found that the ultimate tensile strength exhibits a slight linear increase with hydrogen concentration, which is in good agreement with the experimental results of the low-pressurization-rate burst test at JAERI for the hydrided claddings with zirconium hydride distributed uniformly and with their platelet planes oriented in the circumferential direction of the claddings (see Fig. 7) [2,3]. This implies that the burst test can be modeled as tensile tests for the fully thick specimen that satisfies plane strain fracture.

3.2. Microscopic observation

The occurrence of interfacial debonding, which means that the interface is weak, plays an important role in the fracture behavior and the fracture strength. However, there

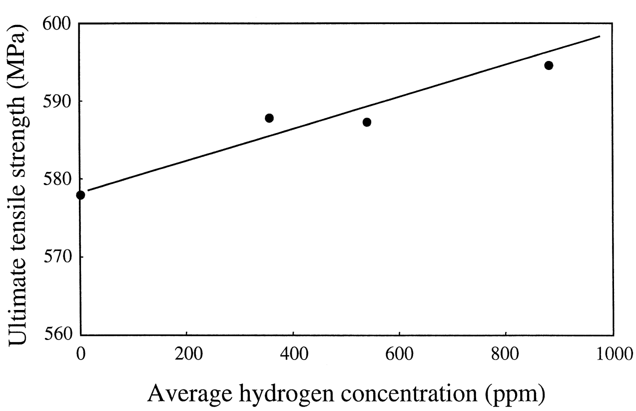

Fig. 6. Influence of average hydrogen concentration on the ultimate tensile strength for the 2.5 mm thickness specimens.

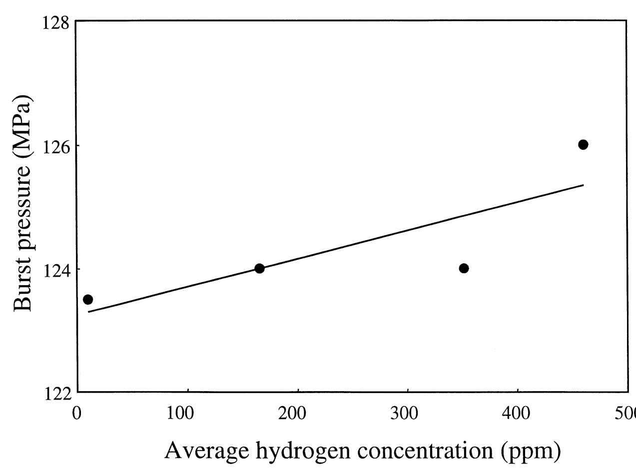

Fig. 7. Burst pressure as a function of average hydrogen concentration with the pressurization-rate of 0.002 $MPa\,ms^{-1}$ [2,3].

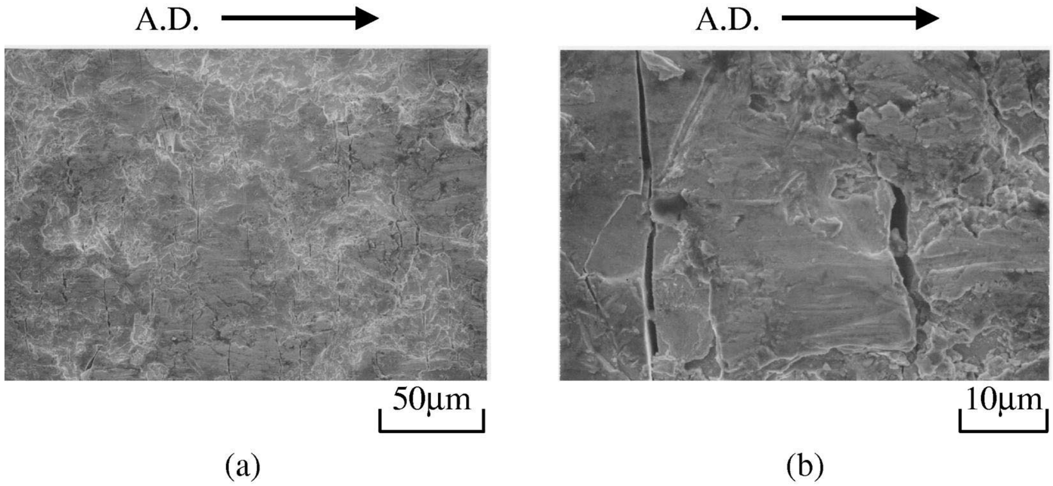

Fig. 8. (a) Typical scanning electron micrograph showing the micro-cracks perpendicular to the axial direction (A.D.) for the hydrided specimen interrupted before ultimate tensile strength. (b) Zoom-up view of the same micrograph.

exists limited information on the matrix/hydride debonding. In the present study, fracture mechanism of the hydrides was examined in detail through microscopic observation of scanning electron microscopy (SEM). Fig. 8 shows the hydrided specimen surface of 1.0 mm thickness with hydrogen concentration of 301 ppm interrupted before the ultimate tensile strength. These photographs indicate that matrix/hydride debonding was not generated but micro-cracks perpendicular to the axial direction were produced. Such micro-cracks were not observed for the non-hydrided specimen beyond the ultimate tensile strength. Therefore, it is assumed that the micro-cracks occurred in the hydride layer, and the hydride failed at relatively low applied stress. Such assumption is consistent with the results of tensile test of solid zirconium hydride ($\delta ZrH_{1.73}$) reported by the present authors [4].

4. Conclusion

In order to estimate the fracture strength under plane strain condition, tensile tests were carried out at room temperature for the non-hydrided and hydrided Zircaloy sheet-type specimens with gauge section of 10.0×5.0 mm and thicknesses of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 mm. The hydrided specimen surface was observed through SEM, and fracture mechanism of the specimen was studied. For the specimens with a thickness more than 2.5 mm, the ultimate tensile strength of the specimens appeared to be independent of thickness, which implied that the plane strain condition was attained. For the specimen with a 2.5-mm thickness, the hydrided specimen with the hydride platelets oriented to the axial direction would be less sensitive to hydrogen embrittlement, and the ultimate tensile strength increased slightly with increasing the average hydrogen concentration. Through microscopic observation of the hydrided specimen surface by SEM, it was found that matrix/hydride debonding was not generated but that micro-cracks perpendicular to the axial direction were produced at the hydride layer.

Acknowledgements

The authors would like to thank Mr. T. Otomo and Mr. K. Kitano of the Department of Reactor Safety Research at the Japan Atomic Energy Research Institute (JAERI) for their experimental assistance. This work was supported by the JAERI.

References

[1] T. Fuketa, H. Sasajima, Y. Mori, K. Ishijima, J. Nucl. Mater. 248 (1997) 249.
[2] F. Nagase, T. Otomo, H. Uetsuka, JAERI-Research 98-064, Japan Atomic Energy Research Institute, 1998 (in Japanese).
[3] T. Fuketa, F. Nagase, T. Nakamura, H. Uetsuka, K. Ishijima, in: 26th Water Reactor Safety Information Meeting, Bethesda, Maryland, Vol. 3, 1998, pp. 223–241, NUREG/CP-0166.
[4] M. Kuroda, K. Yoshioka, S. Yamanaka, H. Anada, F. Nagase, H. Uetsuka, J. Nucl. Sci. Technol 37 (2000) 670.
[5] M. Kuroda, S. Yamanaka, F. Nagase, H. Uetsuka, Nucl. Eng. Des. 203 (2001) 185.
[6] M.P. Puls, Metall. Trans. A 19 (1988) 1507.
[7] M.P. Puls, Metall. Trans. A 22 (1991) 2327.
[8] R. Choubey, M.P. Puls, Metall. Trans. A 25 (1994) 993.
[9] J.B. Bai, C. Prioul, D. Francois, Metall. Trans. A 25 (1994) 1185.
[10] F. Nagase, K. Ishijima, T. Furuta, in: Proceedings of the CSNI Specialist Meeting, Cadarache, France, 1995, pp. 433–443, OCDE/GD(96)197.
[11] M. Grange, J. Besson, E. Andrieu, Metall. Trans. A 31 (2000) 679.
[12] A.S. Tetelman, A.J. McEvily Jr., Fracture of Structural Materials, Wiley, New York, 1967, p. 21.
[13] A.S. Tetelman, A.J. McEvily Jr., Fracture of Structural Materials, Wiley, New York, 1967, p. 96.