# Circumferential Mechanical Properties of HANA Claddings

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## 1. Introduction

Fuel cladding is the key component of the nuclear core for the purpose of protecting the uranium fuel against a flowing coolant. Low-tin Zircaloy-4 has been used for fuel cladding since 1950. Nowadays, minor alloying elements such as niobium, iron, chromium, and copper are added into the zirconium metal in order to enhance the corrosion resistance to keep pace with the high-burnup operation in a nuclear power plant to raise its economy. As the burnup proceeds, an oxide and a subsequent hydrogen content caused by a waterside corrosion are generated in the cladding, which decreases the initial ductility of the cladding [1]. Such oxide and hydrogen act as a negative effect on the cladding safety because the embrittled cladding can lose its ductility and it lowers the margin for a cladding design [2].

The objective in this study is to investigate the effects of absorbed hydrogen on the circumferential mechanical behaviors of a newly developed zirconium alloy cladding. Hydrogen was charged into Zircaloy-4 and zirconium alloy cladding developed by KAERI [3]. Ring tension test and burst test were conducted at the hydrogen-charged cladding and the circumferential mechanical properties such as the strength and fracture strain were evaluated.

## 2. Experimentals

### *2.1. Cladding materials*

Claddings used in this study are the zirconium alloy cladding developed by KAERI. HANA-4 (Zr-1.5Nb-0.4Sn-0.2Fe-0.1Cr) and HANA-6 (Zr-1.1Nb-0.05Cu) cladding were used. Commercial grade low tin Zircaloy-4 (Zr-1.3Sn-0.21Fe-0.1Cr) was also used in this study for a comparison. To simulate the effect of hydrogen, the cladding was cut into the desired length and charged by the Sievert method at a level up to 700ppm.

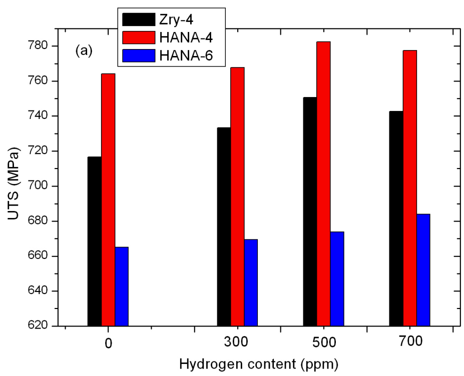
### *2.2. Mechanical tests*

The circumferential ring tension test and biaxial burst test were carried out for the pre-hydride specimen. Hydrogen-charged claddings were cut across their diameter then machined as a ring tension specimen which has a 1.7mm width and 2.11mm gauge length. Strain rates of the ring tension test were 0.01/sec. In the burst test, 150mm of cladding was burst through the expansion of argon gas. General procedure of the burst test followed that of ASTM B811. After the burst test, the maximum hoop stress and maximum circumferential strain at a failure were measured. Microstructures of the fractured specimen were observed using an optical microscope and a Scanning Electron Microscope (SEM).

## 3. Results and Discussions

### *3.1. Effect of the alloying element and the hydrogen content*

Fig. 1(a) shows the circumferential mechanical properties of the zirconium cladding measured by the ring tension test. HANA-4 cladding, which has a large amount of Sn and Nb content, showed the highest strength among the other claddings. As the hydrogen is being charged, it first dissolves into the zirconium matrix to cause a solute hardening. Although a hydride is formed around the zirconium matrix to a certain extent, a solute hardening outweighs it to increase the material strength. For a specimen charged at 700ppm, the hydride embrittlement became so severe that it induced a brittle failure to decrease the material strength. Average increment of the stress with the hydrogen content below 500ppm shows that the hardening effect by hydrogen is the largest in Zircaloy-4, is the smallest in HANA-6. Since Zircaloy-4 contains a large portion of the alpha phase due to a high Sn content, it's susceptibility against hydrogen was higher than any other claddings.



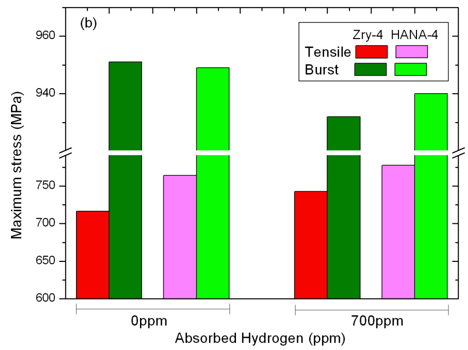



Fig. 1 Circumferential mechanical properties of the zirconium cladding (a) ring tension test (b) burst test

Fig. 1(b) shows the mechanical properties of the hydrided cladding with the burst test. Maximum stress of the burst cladding decreased as the hydrogen content increased. The reason why the maximum stress for the biaxial burst test decreases as the hydrogen content increases could be due to the hydride re-orientation and microvoid growth around the hydride [4]. Effect of an alloying element on the circumferential burst property was relatively small.

### *3.2. Effects of the test temperature*

Fig. 2 shows the effect of the test temperature on the UTS of the zirconium claddings after the ring tension test. From 200$^o$C to 700$^o$C, a dynamic strain aging (abbreviated as DSA) may occur in the zirconium alloy. Mechanism of a DSA in a zirconium alloy [5] revealed that the migration of a vacancy caused by a solution strengthening element such as tin as well as the diffusion of solute atoms such as oxygen interacts with a moving dislocation to cause a DSA. From the analysis between the theoretical stress and actual stress, the magnitude of a DSA in Zircaloy-4 was higher than that in HANA-4. The more tin content is dissolved, the more vacancies are generated inside the zirconium matrix so that a diffusion of a solute atom is easily accommodated to lock the moving dislocation more effectively by virtue of the vacancy generated by tin.

## 4. Conclusions

Ring tension test and burst test for a hydrided cladding were performed to investigate the circumferential mechanical properties of zirconium alloy claddings with the hydrogen content and the following was summarized.

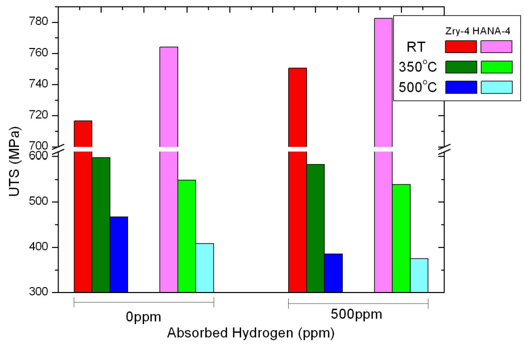



Fig. 2 Ring tension strength of the zirconium alloy cladding with the test temperature.

1. As the hydrogen content increased, an increase in the strength was found in the ring tension test. Zircaloy-4 which contains a large amount of tin showed the highest susceptibility to hydrogen.

2. In the burst test, the maximum stress decreased as the hydrogen content increased. Effect of the stress state was much larger than that of the alloying element.

3. As the test temperature increased, a dynamic strain aging appeared. Hydrogen-charged Zircaloy-4 showed the highest susceptibility at a DSA because of the interaction between dissolved tin and hydrogen.


## Acknowledgement

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