

Delayed Hydride Cracking Velocity of Zr-2.5Nb Pressure Tubes with Hydrogen Concentration

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1. Introduction

Delayed hydride cracking (DHC) velocity of Zr-2.5Nb pressure tubes is one of the material testing items for pressure tube surveillance to be examined regularly. Thus, it is required to establish a model to accurately predict the DHC velocity with operating conditions. According to our new DHC model called Kim's model [1], the DHC velocity is governed by the supersaturated hydrogen concentration above the heating solvus or the terminal solid solubility for dissolution of hydrogen (TSSD) or ΔC at the test temperature. However, by arguing that the DHC velocity increased with increasing hydrogen concentration dissolved in the bulk, not the ΔC , Shek [2] pointed out that Kim's model is invalid. The aim of this work is to show the validity of Kim's model by checking if the DHC velocity of the Zr-2.5Nb tube is governed either by total hydrogen concentration dissolved in the bulk as suggested by Shek or by the ΔC as shown in Kim's DHC model.

2. Experimental procedures

DHC tests were conducted on cold-worked Zr-2.5Nb tubes at 182 °C upon an approach by cooling from the peak temperatures. The peak temperatures were set at 10 °C above the TSSD temperatures to completely dissolve the hydrides in the bulk. 17 mm compact tension (CT) and cantilever beam (CB) specimens were used to measure the DHC velocity in the axial and radial direction of the Zr-2.5Nb pressure tube. To see a hydrogen concentration dependence of the DHC velocity, both specimens were precharged to 6 to 100 ppm of hydrogen using an electrolytic charging method. Details of the DHC test method are given elsewhere [3].

3. Results and discussion

Fig. 1 shows the DHC velocity of a Zr-2.5Nb tube at 182 °C as with charged hydrogen concentration: it increased with increasing hydrogen concentration and leveled off to a constant at or above 30 ppm H. To check if this hydrogen concentration dependence of the DHC velocity holds true at different temperatures, Sagat's data obtained at 200 and 250 °C were additionally plotted as shown in Fig. 1 [4]. The constant DHC velocity at or above 40 ppm H was also observed at 200 °C. However, this hydrogen concentration dependence of the DHC velocity was not observed at 250 °C where DHC velocity increased with

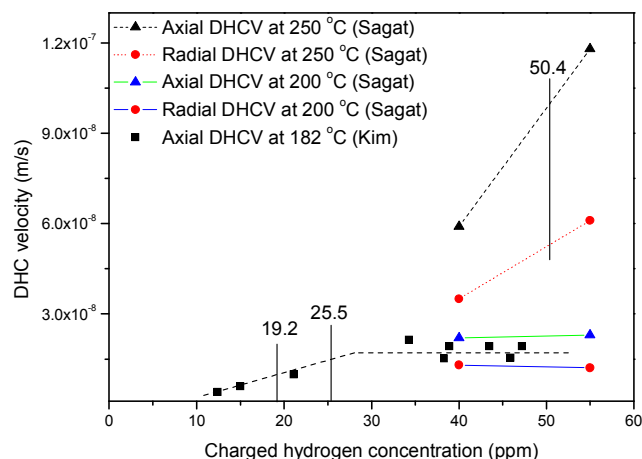


Fig. 1. DHC velocity of Zr-2.5Nb tubes with charged hydrogen concentration at three different temperatures.

increasing hydrogen concentration even at the charged hydrogen concentration above 40 ppm H. Considering that the charged hydrogen concentration was fully dissolved in the bulk at the peak temperature before cooling to the test temperatures, the results shown in Fig. 1 reveal that no consistent relationship between the DHC velocity and hydrogen concentration dissolved in the bulk exist at all the test temperatures. This fact demonstrates that Shek's argument [2] that the DHC velocity of zirconium alloys increases with hydrogen concentration in solution in the bulk is irrational. To check the feasibility of Shek's hypothesis that the DHC velocity of zirconium alloys would be highest with the bulk hydrogen concentration increasing to the terminal solid solubility for precipitation (TSSP), the TSSP2 at each test temperature, corresponding to the cooling solvus for hydride growth, is inserted as a line along with the number. As shown in Fig. 1, it is obvious that the maximum DHC velocity does not agree with the TSSP at all the test temperatures but occurs above the TSSP. This fact definitively demonstrates that Shek's hypothesis where the DHC velocity is governed by hydrogen concentration in solution is faulty.

According to Kim's DHC model, the DHC velocity of zirconium alloys is governed by the supersaturated hydrogen concentration above the TSSD or ΔC at a test temperature, not by the bulk hydrogen concentration in solution. Hence, the DHC velocity of Zr-2.5Nb tubes shown in Fig. 1 was plotted again as a function of the ΔC . The DHC velocity increased with the ΔC and leveled off to a constant value above 20 to 25 ppm H at all the test temperatures. Thus, when DHC velocity

dependence on the bulk hydrogen concentration occurred only at 250 °C, not at lower temperatures than that is due to the ΔC effect. Given that the TSSD increases with the test temperatures, the supersaturated hydrogen concentration decreases with increasing test temperatures even at the same hydrogen concentration charged in the bulk.

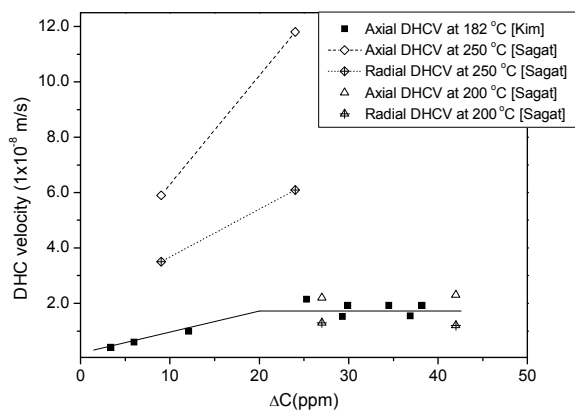


Fig. 2. DHC velocity of Zr-2.5Nb tubes with ΔC , the supersaturated hydrogen concentration over the TSSD.

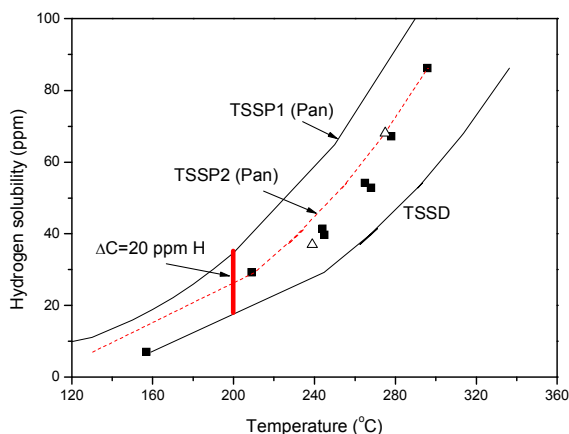


Fig. 3. Hydrogen solubility for Zr-2.5Nb alloy on heating and cooling: TSSP1 and TSSP2 correspond to the cooling solvi of hydrides for nucleation and for growth, respectively.

It should be noted that the difference between the TSSP1 and the TSSD corresponds to around 20 ppm H as shown in Fig. 3. Given that the DHC velocities of the Zr-2.5Nb tubes become flat at 20 to 25 ppm H, the maximum supersaturation of hydrogen over which the DHC velocity becomes flat corresponds to TSSP1 minus TSSD.

4. Conclusions

When plotted as a function of the charged hydrogen concentration, no consistent relationship between the DHC velocity and the bulk hydrogen concentration in solution was observed at all the test temperatures. This

fact reveals that the old DHC model where the DHC velocity is governed by the bulk hydrogen concentration in solution is faulty. The DHC velocity of the Zr-2.5Nb tube increased with increasing supersaturated hydrogen concentration and became flat when the ΔC exceeds 20 to 25 ppm H, or ΔC_{max} . By comparing the ΔC_{max} with the difference in the Zr-2.5Nb tube between the cooling solvus and the heating solvus, it is found that the ΔC_{max} over which the DHC velocity becomes flat corresponds to the TSSP1-TSSD. Consequently, this study provides evidence for the validity of Kim's DHC model.

ACKNOWLEDGEMENTS

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