THE INFLUENCE OF HYDROGEN CONCENTRATION ON THE RAMBERG-OSGOOD CONSTITUTIVE EQUATION FOR ZR-2.5%NB PRESSURE TUBE ALLOY

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Abstract

In the present paper is revealed an important aspect of the systematic approach of the structural integrity assessment of the CANDU pressure tube Zr-2.5% Nb alloy. The objective is focused on the determination of the material properties characterizing the stress-strain behavior, under conditions of hydrogen absorption in the material. Experimental investigations from present paper are based on the tensile tests by using the Walter +Bai mechanical test facility at room temperature. In order to evaluate the mechanical properties of the Zr-2.5% Nb alloy a specific specimens called “dog-bone” were used. These kinds of specimens were prepared from the circumferential direction of the CANDU pressure tube. Following the tensile tests, the primary traction curves were obtained, and subsequently, by processing them, the values of the parameters of interest as well as the parameters of the Ramberg-Osgood equation have been inferred. The results of the paper are useful in the development of the theoretical framework and the practical application of the methods assessing the integrity of pressure tubes in the CANDU fuel channels from the Cernavoda Nuclear Power Plant. The fitness-for-service assessment of CANDU pressure tube taking into account the in-service inspection results and it is based on the procedural framework of the standard Canadian CAN/ CSA N285.8-05.

Keywords: *Tensile tests, DHC, “dog-bone” specimens, Ramberg-Osgood equation*

Introduction

In CANDU reactors, during normal operation, the pressure tubes are subjected to the various degradation mechanisms that may develop the crack flaws on the inner surface. The probability of a crack being present is quite high due to the corrosion phenomenon, the flow-induced vibration by the fuel bundles and the precipitation of the hydride platelets by the continuous absorption of deuterium in the Zr matrix. Delayed Hydride Cracking (DHC) is the main damaging phenomenon, which can affect the life of CANDU pressure tubes when absorbed deuterium becomes greater than the equivalent hydrogen solubility, at the operation temperatures [1].

The overall objective of the paper is focused on the determination of material properties characterizing the Zr-2.5% Nb alloy stress-strain behavior, under conditions of the hydrogen absorption in the material. The experimental investigations are based on the tensile tests in order to evaluate the mechanical properties of the Zr-2.5% Nb alloy and by using the Walter+ Bai mechanical test facility at room temperature. Following the tensile tests, the primary loading curves were obtained, and subsequently, by processing them, the values of the parameters of interest as well as the parameters of the Ramberg-Osgood equation [2] have been inferred.

The tensile test results revealed that the Zr-2.5% Nb alloy is "hardened" by the absorption of hydrogen and its precipitation as the hydride platelets. Thus, the mechanical strain and the strength values increase quite a lot with increasing the hydrogen concentration. At the same time, the ductility decreases, and this is observed in the low values of the deformation at fracture. As far as the Ramberg-Osgood parameter values are concerned, it can be seen that the influence of hydrogen uptake in mainly to the hardening exponent (n), while the material parameter (α) remains almost constant.

The metallographic and SEM analyses have highlighted the fact that although the hydrides platelets remain in the circumferential direction of the pressure tube they still affect the behavior of the material. Therefore, they promote the initiation and subsequent the propagation of the crack (DHC mechanism); the behavior of the "ductile-fragile mixture" is even more evident in SEM analyses of the crack surface.

The results of the paper are useful in the development of the theoretical framework and the practical application of the methods for assessing the integrity of Zr-2.5% Nb alloy pressure tubes in CANDU fuel channels from the Cernavoda Nuclear Power Plant, based on the in-service inspection results and the methodology from the standard Canadian CAN/ CSA N285.8-05 [3].

Experimental activity

The experimental tensile tests were performed on specimens with different levels of hydrogen concentration in order to evaluate the stress-strain behaviour of the Zr-2.5% Nb alloy.

Several steps are described below:
• The specimens were prepared in a typical "dog-bone" shape from the circumferential direction of the CANDU pressure tube,Zr-2.5% Nb alloy (see Figure 1);
• The specimens were subjected to a thermal treatment of localized hydrides under constant mechanical stress in concentration range of 30-60 ppm, which means normal conditions of the pressure tube for operating in the reactor;
• After hydrogen determination, the experimental tensile tests were performed by using the Walter +Bai mechanical test facility (see Figure 2) at room temperature.



Fig. 1. The "dog-bone" specimen



Fig. 1. The "dog-bone" specimen

Following the tensile tests, the primary tensile curves were obtained. After their processing, the parameters of interest as well as the parameters of the Ramberg-Osgood equation have been inferred, [2]:

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha \cdot \left(\frac{\sigma}{\sigma_0}\right)^n \qquad (1)$$

with: σ_0– yield stress; ε_0 – corresponding deformation ($\varepsilon_0 = \sigma_0/E$, E –Young modulus); n – hardening exponent; α - material parameter.

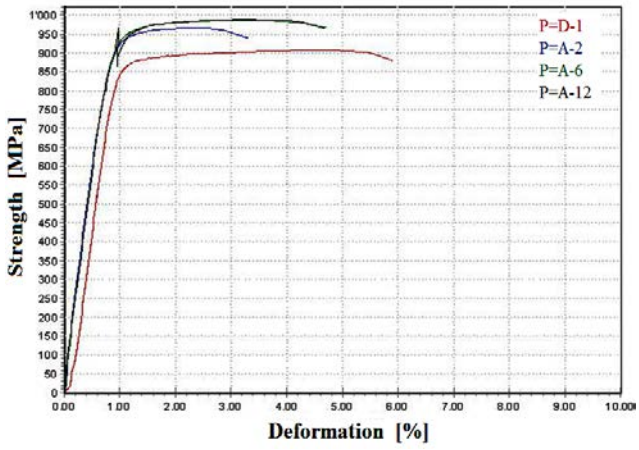


Fig. 3. The mechanical strain - deformation curve

As it is shown in Figure 3, the tensile test results revealed that the Zr-2.5% Nb alloy is "hardened" by the absorption of hydrogen and its precipitation as the hydride platelets. Thus, the mechanical strain and the strength values increase quite a lot with increasing the hydrogen concentration. Meanwhile, the ductility decreases for the low values of the deformation at fracture.

Processing of the experimental results

The fracture surface and crack propagation measurements were performed by using the metallographic examination, being illustrated in Figure 4.

The behaviour of the "ductile-fragile mixture" is even more evident in SEM analyses of the crack surface, as can be noticed in Figure 5.

The SEM examination direction is perpendicular to the crack surface. One may see the voids, which are typical of the ductile matrix fracture of the zirconium alloy, which interferes with the trans-granular fragile fracture characteristics.
In the case of the 60 ppm concentration (Figure 5c), the trans-granular breaking planes can even be the planes of some hydrides, which exhibit low cohesion in the case of a mechanical stress that develops tri-axially in the collapse zone of the active area of the specimen.

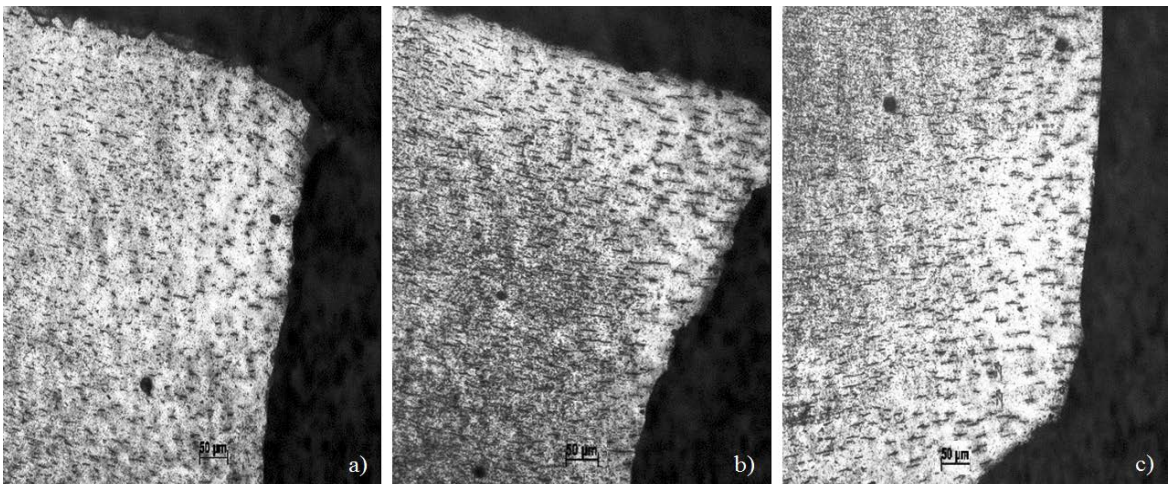


Fig. 4. Metallographic examination of the specimen surface after test for: a) 36 ppm; b) 45 ppm; c) 60 ppm

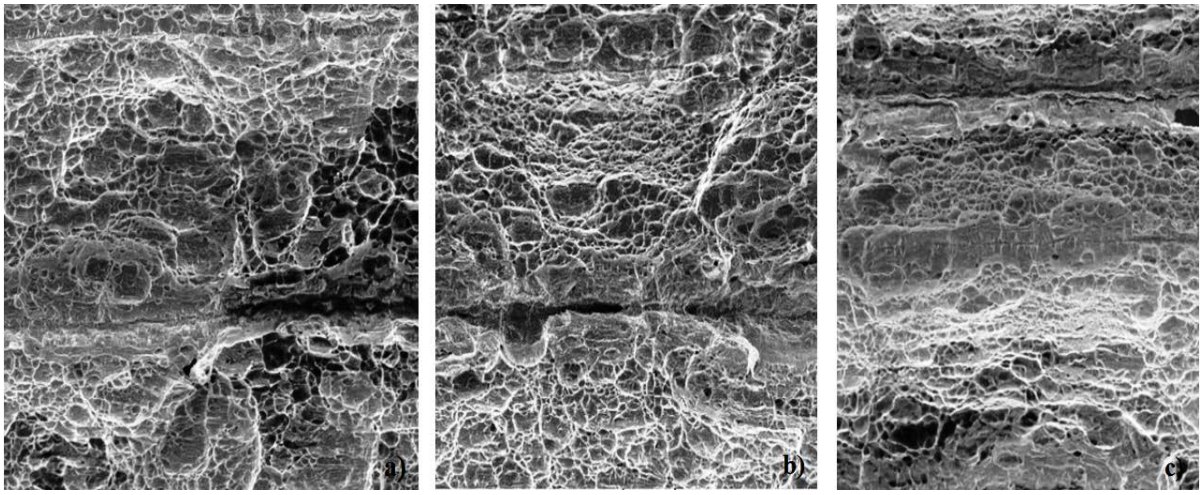


Fig. 5. SEM examination of the cracking hydride surface for: a) 36 ppm (x1000); b) 45 ppm (x1000); c) 60 ppm (x1000)

Conclusions

The main objective of the paper was the determination of material properties characterizing the Zr-2.5% Nb alloy stress-strain behaviour in the hydrogen concentration range 30 - 60 ppm.

The tensile test results have shown that the Zr-2.5% Nb alloy is "hardened" by the absorption of hydrogen and its precipitation in the form of hydride platelets.

The Ramberg-Osgood parameters were inferred; they characterize the stress-strain constitutive behavior, and one may see the influence of hydrogen uptake mainly to the hardening exponent (n), while the material parameter (α) remains almost constant.

Metallographic and SEM analyses have highlighted the fact that although the hydrides remain in the circumferential direction of the pressure tube, they still affect the fracture behaviour of the material. The cracking direction remains normal to the loading, with small ductile areas inside of 45º to the load direction.

The ductile-fragile behavior is even more evident in the SEM analyses of the fracture surfaces. From the SEM examination of the crack surface one may see the voids coalescence, which is typical for the ductile zirconium matrix, and their interference with the trans-granular fracture characteristics of the brittle fracture.

The paper approach is foreseen to be implemented in the Post-Irradiation Examination Laboratory at Institute for Nuclear Research Pitesti, on the irradiated material cut from removed pressure tubes in Cernavoda NPP. The experimental results will be used to build-up a database to perform the structural integrity assessment activities based on in-service inspection results.

References

[1] Puls, M. (1994) "Delayed Hydride Cracking in Zr-2.5%Nb Alloy", IAEA Specialists meet., Vienna, Austria

[2] Anderson, T.L. (1995) "Fracture Mechanics, Fundamentals and Applications", CRC Press

[3] *** (2005) CAN/CSA Standard N285.8-05 "Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors", Standard Council of Canada