Optimization of the Manufacturing Process of Zr-2.5Nb Pressure Tubes for CANDU[1] Reactors for Extending Their Design Life to Over 30 years

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1. Introduction

Zr-2.5Nb pressure tubes are the most critical components that determine the design life of CANADU (CAnadian Natural Uranium) reactors. The initial design target for the Zr-2.5Nb pressure tubes is to suppress the diametral creep through a texture control which may trade off the other performances that can be overcome by introducing a change in the components design. To this end, they are made by the extrusion process at high temperatures to have a circumferential texture with most of the basal poles oriented towards their circumferential direction. However, this circumferential texture causes them to be very susceptible to delayed hydride cracking (DHC) [1] and to have a higher axial elongation [2]. Against the initial design target, their costly refurbishments are planned in several commercial CANDU reactors before their design life of 30 years, due to the unexpectedly faster creep rate and axial elongation. This fact casts a question over the validity of the design philosophy that the diametral creep of the Zr-2.5Nb pressure tube is governed by the texture. The aim of this work is to elucidate the governing factor of creep of the Zr-2.5Nb tubes and to find a way of making improved Zr-2.5Nb pressure tubes with a lower diametral creep and axial elongation. To this end, we scrutinized Holt's experiment where the in-reactor creep behaviors of the Zr-2.5Nb micro-pressure tube (MPT) with a circumferential texture was compared with that of the Zr-2.5Nb fuel sheath (FS) with a radial texture. Accounting for the fact that thermal creep of Zr-2.5Nb alloy is affected by the Nb concentration in the β-Zr, we demonstrate that the reduced creep is not dictated by the circumferential texture but by the increased Nb concentration in the α-Zr. This study suggests that the optimized manufacturing procedure of the Zr-2.5Nb tube would improve their in-reactor performances, extending their design life to over 30 years when compared to that of the current design of the cold-worked Zr-2.5Nb pressure tube.

2. Results and Discussion

Fidleris [3] showed that when the creep tests were conducted on the specimens taken from the short transverse (or normal), longitudinal and transverse directions of the Zircaloy sheet, the highest creep strains occurred in the short transverse direction at 300 ^oC under 207 MPa. Considering that the short transverse direction has the highest density of the basal pole as with the circumferential direction of the Zr-2.5Nb tube, the highest creep strains at 300 ^oC in the short transverse directions is in contradiction with Holt's argument [2] that the circumferential texture would suppress the in-reactor diametral creep of the Zr-2.5Nb tubes. Based on this observation, Fidleris suggested that the creep anisotropy of the zirconium alloys due to the texture effect may disappear at a high temperature as 300 ^oC [3].

Using two micro-tubes of Zr-2.5Nb alloy with different textures, as shown in Fig. 1, Holt [2] showed that the Zr-2.5Nb MPT of the reduced diameter with a strong circumferential texture as with the real Zr-2.5Nb pressure tubes had lower diametral creep strains and rates than the Zr-2.5Nb FS with a radial texture when tested at 583 K in a high flux reactor with fluences increasing to over $15x10^{25}$ n/m^2 (E>1MeV). However, it should be noted that the Zr-2.5Nb MPT with a circumferential texture has a very high axial strains but the Zr-2.5Nb FS with a radial texture exhibits a very low elongation close to zero. Ostensibly, this result indicates that the tangential texture lowers the diametral creep strains and rates but enhances the axial elongation when compared to the radial texture. Besides, it suggests that the design philosophy of the Zr-2.5Nb pressure tube developed by Canadian workers is feasible.

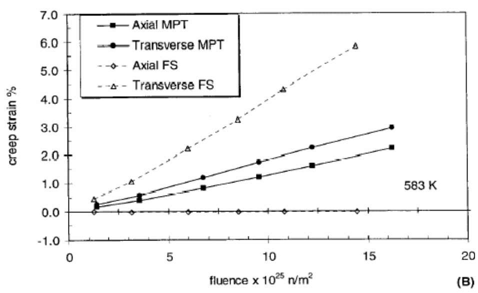

Fig. 1. A change of diametral creep strains as a function of neutron fluence for the micro Zr-2.5Nb pressure tube (MPT) with a circumferential texture and the Zr-2.5Nb fuel sheath (FS) with a radial texture (E>1MeV) which were irradiated at 583 K in a high flux reactor [2]..

However, they have overlooked the fact that the two micro-tubes of Zr-2.5Nb alloy have different microstructures due to different manufacturing procedures. Their final annealing treatments were different: full annealing at 502 ^oC for 6h for the MPT and a stress relieving treatment at 400 ^oC for 24h for the

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FS. These different final annealing treatments cause them to have different Nb concentrations in the β-Zr grains as well as their distribution. It is clear that thermal treatment at as high a temperature as 500 °C for 6h decompose the β-Zr into the fully discontinuous β-Nb [4], as in Fig. 2 given in Ref. [5], and annealing treatment at 400 °C for 24h contributes to little decomposition of the β-Zr phase [4], allowing it to maintain a semi-continuous distribution, as in Fig. 3 given in Ref. [5]. In other words, they have disregarded the effect of decomposition of the β-Zr on the creep.

In contrast, Kim [6] has demonstrated that in-reactor creep of the cold worked Zr-2.5Nb pressure tube is governed by the Nb concentration in the β-Zr or decomposition of the β-Zr, by correlating the diametral creep profile with the distance from the inlet with an axial distribution of the Nb concentration in the β-Zr. Besides, through the model experiment where the creep tests were conducted using the Zr-2.5Nb sheet specimens with different Nb concentration in the β-Zr, it was demonstrated that the higher the Nb concentrations in the β-Zr, the faster the thermal creep of the Zr-2.5Nb alloy as shown in Fig. 2 [6]. It should be noted that an increased Nb concentration in the β-Zr as a result of thermal decomposition concurrently involves a small decrease in the Nb concentration in the α-Zr with a larger volume fraction. Thus, the experimental fact that in-reactor and thermal creep of the Zr-2.5 Nb is dictated by the Nb concentrations in the β-Zr indicates that the in-reactor creep of the Zr-2.5Nb tube is governed by the Nb concentration in the α-Zr. This rationale is reasonable because the α-Zr dominates the mechanical properties of the Zr-2.5Nb tubes due to its larger volume fraction of around 90%.

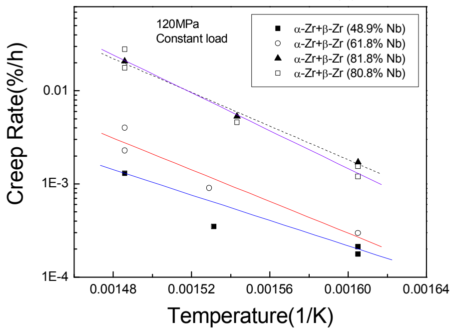

Fig. 2. Creep rate of the Zr-2.5Nb sheet with different Nb concentrations in the β-Zr with the applied stress of 120 MPa at 350-400 °C [6].

In other words, Kim's creep test results on the Zr-2.5Nb specimens, as shown in Fig. 2, indicate that the Nb concentration in the α-Zr must be a very influential factor to govern thermal creep and in-reactor creep of the Zr-2.5Nb tube. Considering Kim's experimental results [6], at least, Holt should have included not only the texture effect but also the effect of the Nb concentration in the α-Zr when comparing in-reactor creep of the Zr-2.5Nb tubes with different textures. Accordingly, the enhanced diametral creep of the Zr-2.5Nb tube with a radial texture shown in Fig. 1 must be caused by the combined effects of the lower Nb concentration in the α-Zr and the radial texture, if any. When account is taken of no texture effect on thermal creep of zirconium alloys at 300 °C as observed by Fidleris [3], it is more reasonable to conclude that the former dominantly governs the in-reactor creep of the Zr-2.5Nb tube when compared to the latter. In short, the solution hardening of the α-Zr by niobium is likely the main mechanism of creep of the Zr-2.5Nb tube irrespective of texture. Experimental evidence for little texture effect on creep is provided by Coleman' data [7] where a TMT-2 Zr-2.5Nb tube with a slightly reduced circumferential texture had a lower in-reactor creep strains than a cold-worked Zr-2.5Nb with a higher circumferential texture. Therefore, the manufacturing processes of the Zr-2.5Nb tube for CANDU reactors should be optimized not to have a strong circumferential texture as with the current pressure tubes but similar to that of the TMT-2 tube with a less strong circumferential texture. The optimized manufacturing processes also increases fracture toughness and resistance to DHC which increases the safety margin for the leak-before-break criterion, thus providing more flexibility for the operation of CANDU plants and extending the design life to over 30 years.

3. Conclusion

When account is taken of the solution hardening of the α-Zr by niobium due to a difference in their final annealing treatments and of little texture effect of creep reported by others, the enhanced creep of the Zr-2.5Nb FS with a radial texture is concluded to be not due to the texture effect but due to reduced Nb concentrations in the α-Zr. Consequently, it is recommended that the manufacturing process of the pressure tubes should be optimized to be similar to the manufacturing processes of the TMT-2 Zr-2.5Nb tube, which can contribute to extending their design life to over 30 years.

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