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Letter to the Editors

Anisotropy of in-reactor deformation of Zr–2.5Nb pressure tubes

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Abstract

Theoretical modeling and results from irradiation experiments show that the diametral strain rate of an internally pressurized (closed end) cold-worked Zr-2.5Nb tube increases as the resolved fraction of basal plane normals, f, increases in the radial direction and reduces in the transverse direction. At the same time the elongation rate decreases. The increased diametral strain rate results from an increased diametral creep rate, and a decreased (in magnitude) negative diametral irradiation growth rate. The decreased elongation rate results from a reduction in the axial creep component under the biaxial stress conditions.

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1. Introduction

In a recent publication Kim and Kim [1] have verified that K_{IH} for delayed hydride cracking (DHC) in CANDU pressure tubes (PT) can be increased if the crystallographic texture is modified to increase the fraction of basal plane normals in the radial direction of the tube. Such a modification had previously been proposed to increase the tolerance for DHC initiation of PT in CANDU reactors [2]. In this note, we examine the implications of such a modification for another potential life-limiting factor in CANDU PT – the diametral strain rate. We report experimental data and calculations illustrating the effect of texture on the anisotropy of the in-reactor deformation of Zr–2.5Nb tubes.

2. Materials

The materials discussed here are 104 mm diameter CANDU Zr–2.5Nb PT and 10 mm diameter Zr–2.5Nb tubes of two different textures. The latter, used for in-reactor creep tests, are referred to as micropressure tubes (MPT) and fuel sheathing (FS). The manufacturing procedures of these materials and their microstructures were described earlier [3,4]. The average values of the resolved fraction of basal plane normals, f_R, f_T and f_L in the radial (R), transverse (T) and axial (A) directions of the tubes are given in Table 1, and basal pole figures are shown in Fig. 1. The fabrication procedure for the MPT was similar to that used for standard PT, and the texture and grain structures are therefore similar.

3. Model calculations

Tomé et al. [5] developed a self-consistent polycrystalline approach to predict the anisotropy of in-reactor deformation from crystallographic texture.

Christodoulou et al. [6,7] extended this approach to predict the dependence of the in-reactor creep compliances of polycrystalline Zr–2.5Nb on the crystallographic texture using an empirically determined single crystal creep compliance tensor. This model has been used to calculate the biaxial creep compliances, B_T, B_A, and B_R in the three tube directions for a range of real

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Table 1
Resolved fraction of basal plane normals of materials considered in this study

Material	f_R	f_T	f_L	$f_T - f_R$
PT (front end)	0.30	0.64	0.06	0.34
PT (back end)	0.36	0.60	0.04	0.24
MPT	0.34	0.57	0.09	0.23
FS	0.56	0.37	0.07	−0.19

textures. These creep compliances are proportional to the creep strains in the three directions under biaxial loading conditions (the transverse stress is twice the axial stress and the radial stress is zero). For wrought zirconium alloy tubes, f_L is always small, the major variation in texture is the distribution of basal plane normals in the radial-transverse plane and the anisotropy can be correlated with the variable $f_T - f_R$. Fig. 2 shows the calculated dependence of the three compliances (points) as a function of $f_T - f_R$ and trend lines for the three quantities. For the materials cited above, $f_T - f_R$ varies from −0.19 to 0.34 for the FS and the PT materials respectively. It is evident that the transverse creep compliance, B_T, is substantially higher for the FS than for the MPT and PT material. For the same range of values of $f_T - f_R$, the axial creep compliance, B_A, varies from negative to positive.

In Ref. [7] irradiation growth was calculated based on an empirical single crystal growth rate tensor that was assumed to be identical for all orientations. It is now known, however, that the dislocation substructure within each component crystal of a polycrystal depends upon its orientation, in both Zircaloy-2 [8,9], and Zr–2.5Nb [10]. The growth rate tensor would therefore also depend upon the orientation of the crystal. Tomé and Christodoulou [11] have successfully modeled the deformation of Zr–2.5Nb, using the theoretical single crystal growth anisotropy exhibiting isotropic expansion in the basal plane and contraction along the *c*-axis. The magnitude of the growth rate tensor varied with orientation depending upon the observed variation in dislocation substructure.

To illustrate the qualitative effect of texture on growth anisotropy, we have used the theoretical growth anisotropy. However, with no observed dislocation substructures, the magnitude of the growth rate tensor must be assumed to be the same for all crystals. The calculated polycrystalline growth rates for the same

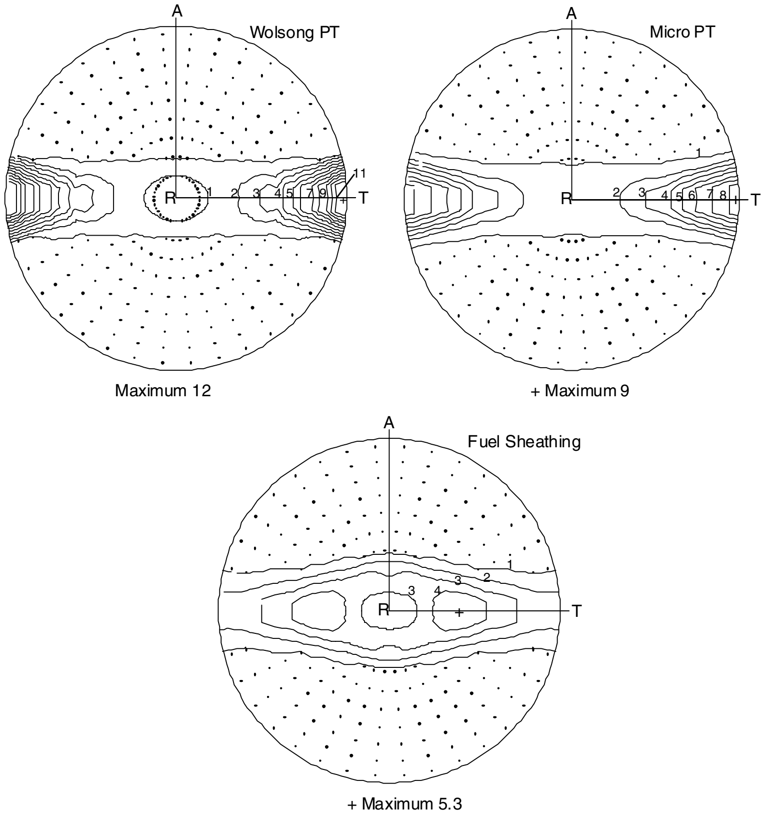

Fig. 1. Basal pole figures of: above left – a CANDU PT, above right – a MPT, and below – FS.

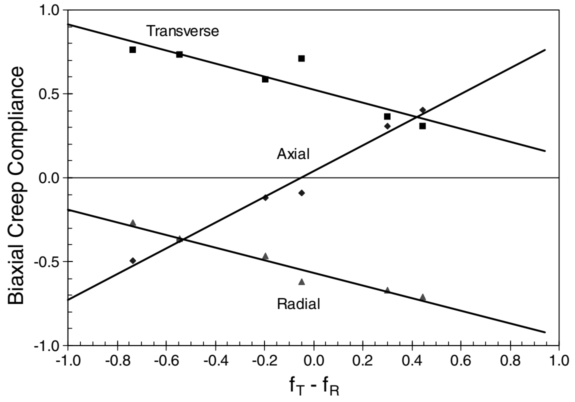

Fig. 2. Predicted dependence of the creep compliance (arbitrary units) in the radial, transverse and axial directions of Zr–2.5Nb materials on the texture parameter, $f_T - f_R$.

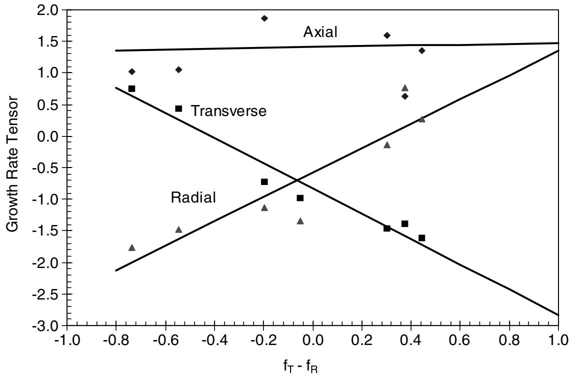

Fig. 3. Predicted dependence of the growth strain-rate tensor (arbitary units) in the radial, transverse and axial directions of Zr–2.5Nb materials on the texture parameter, $f_T - f_R$.

set of real textures used to calculate the creep compliances are shown in Fig. 3. Here the growth rate varies substantially only in the transverse and radial directions, while the growth rate in the axial direction is insensitive to $f_T - f_R$.

From this calculation, the PT and MPT are expected to have a larger negative growth rate in the transverse direction than the FC, making a further contribution to a lower transverse strain rate.

4. In reactor tests

Biaxial irradiation creep tests were performed on the MPT and FC materials in the Osiris reactor at Saclay, France at nominal temperatures of 553 and 583 K in a peak fast neutron flux of 1.8×10^{18} $\mathrm{n\,m^{-2}\,s^{-1}}$, $E > 1$ MeV, to a fast neutron fluence of 1.7×10^{26} $\mathrm{n\,m^{-2}}$, $E > 1$ MeV. The experiments are described in detail in Refs. [3,4]. The specimens were internally pressurized tubular capsules with 10.0 mm in external diameter, 0.45 mm wall thickness and 46.4 mm gauge length. The nominal tangential stresses varied from 0 to 160 MPa, and the axial stress was half the tangential stress. Measurements of diameter and length were made periodically when the specimens were removed from the reactor, using a computer controlled, under-water measuring bench equipped with LVDT (linearly variable differential transformer) probes to measure diameter at six axial and 200 circumferential locations and length at 200 circumferential locations.

The results of these tests for specimens with tangential stresses of zero (representing irradiation growth) and 160 MPa (representing a combination of creep plus growth) are shown in Figs. 4 and 5. The actual stresses and temperatures for these specimens are shown in Table 2.

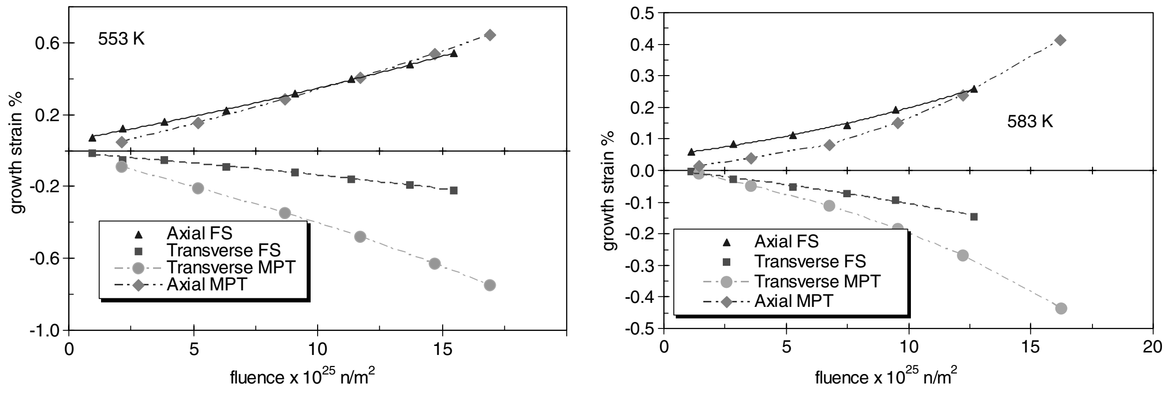

Fig. 4. Axial and transverse growth strains for unstressed capsules irradiated in Osiris at nominal temperatures of A – 553 and B – 583 K.

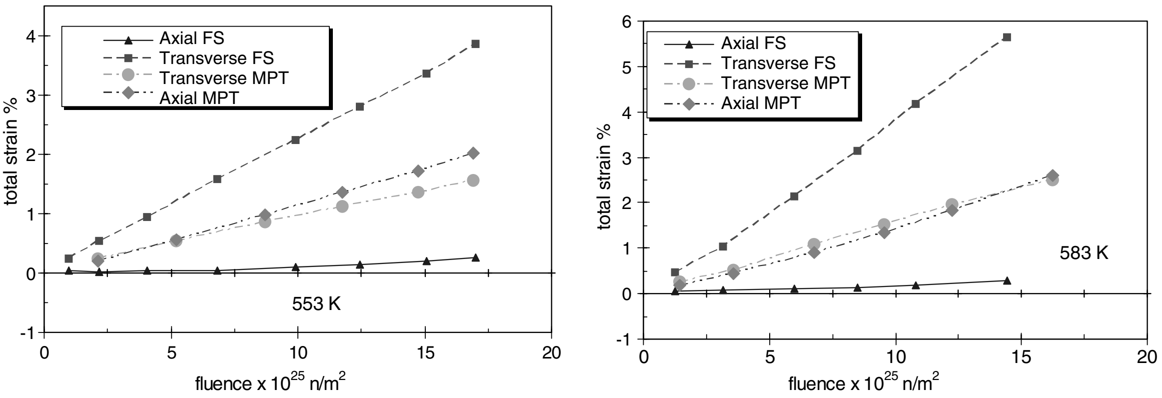

Fig. 5. Total axial and transverse strains for stressed capsules (160 MPa) irradiated in Osiris at nominal temperatures of A – 553 and B – 583 K.

Table 2
Operating conditions for the tests in Osiris

Material	Nominal T (K)	Nominal stress (MPa)	Actual T (K)[a]	Actual stress (MPa)
MPT	553	0	537	0
		160	554	160
	583	0	584	0
		160	585	161
FC	553	0	564	0
		160	554	147
	583	0	589	0
		160	586	154

[a] Time averaged.

To determine the magnitude of creep alone, the irradiation growth strain was interpolated with respect to fast neutron fluence by fitting a quadratic equation to the data for each of the unstressed specimens in Fig. 4, and subtracting that from the total strain for the stressed specimens in Fig. 5. This supposes that creep and growth are additive [6]. The results are shown in Fig. 6.

The important points to note are:

- the total diametral strains of the stressed FS specimens are at least double those of the stressed MPT specimens at high fast neutron fluences, and there is a contribution from growth which has a smaller (negative) magnitude in the FS specimens as well as creep which is ~1.8 times greater for the FS specimens. The difference in creep would be slightly larger if the stresses in the two sets of specimens were identical.
- The total axial strains of the MPT specimens are almost 10 times those of the FS specimens at high fast neutron fluences. In this case the growth strains of

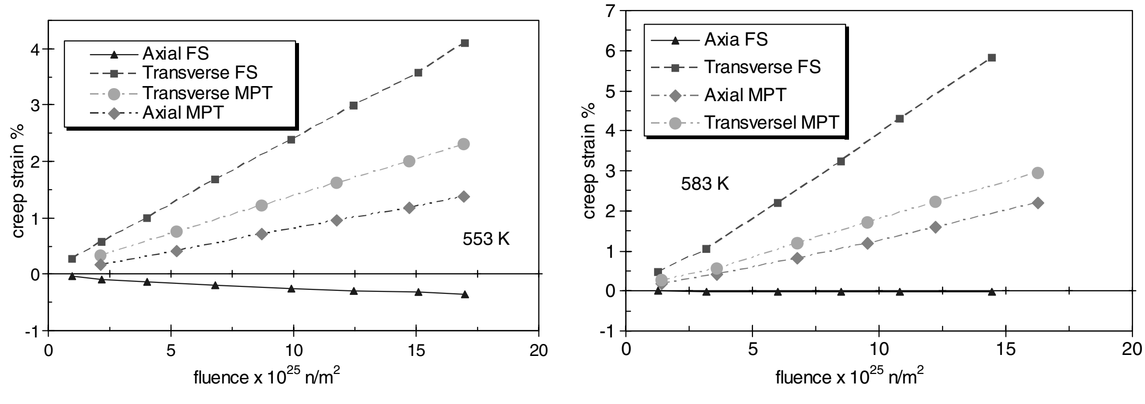

Fig. 6. Derived axial and transverse creep strains for stressed capsules (160 MPa) irradiated in Osiris at nominal temperatures of A – 553 and B – 583 K.

the two materials are very similar, and the difference is mainly due to creep. The difference in axial strain would be slightly larger if the stresses in the two sets of specimens were identical.

5. Implications

From the results presented above, it is clear that the typical variation in texture in a wrought tube, i.e., differing distributions of the basal plane normals in the radial-transverse plane, creates a trade-off between transverse and axial strain. As the distribution shifts towards the radial direction, the transverse strain rate increases, and axial strain rate decreases. This is born out by both the model calculations and the experimental observations.

In a CANDU reactor, the axial strain (elongation) of the PT is accommodated by the design of the end hardware [12]. However, transverse strain (increase in diameter) is not so easily accommodated. As the reactor ages and the PT diameter increases, the coolant increasingly bypasses the fuel, reducing its efficiency at extracting heat [13]. A thermohydraulic limit will ultimately be reached that limits the power output of the reactor. This limit will be reached much earlier with a PT with a radial texture.

Finally, although no firm diametral creep limit has been established with respect to PT integrity, 5% has been suggested as a ‘very conservative’ criterion [14] to which reactors can operate. The current PT in CANDU reactors will certainly approach 5% strain by end-of-life. A change in texture that would double this strain would require an extensive program to verify that PT integrity would not be affected.

References

[1] S.S. Kim, Y.S. Kim, J. Nucl. Mater. 279 (2000) 286.
[2] C.E. Coleman, B.A. Cheadle, C.D. Cann, J.R. Theaker, ASTM STP 1295, American Society for Testing and Materials, West Comshohocken, 1996, p. 884.
[3] A.R. Causey, J.E. Elder, R.A. Holt, R.G. Fleck, ASTM STP1245, American Society for Testing and Materials, Philadelphia, 1994, p. 202.
[4] A.R. Causey, R.A. Holt, N. Christodoulou, E.T.C. Ho, ASTM STP-1354, American Society for Testing and Materials, West Comshohocken, 2000, p. 74.
[5] C.N. Tomé, C.-B. So, C.H. Woo, Philos . Mag. 67 (1993) 917.
[6] N. Christodoulou, A.R. Causey, C.H. Woo, C.N. Tomé, R.J. Klassen, R.A. Holt, ASTM STP1175, American Society for Testing and Materials, Philadelphia, 1993, p. 1111.
[7] N. Christodoulou, A.R. Causey, R.A. Holt, C.N. Tomé, N. Badie, R.J. Klassen, R. Sauvé, C.H. Woo, ASTM STP1295, American Society for Testing and Materials, West Comshohocken, 1996, p. 518.
[8] M. Griffiths, R.A. Holt, A. Rogerson, J. Nucl. Mater. 225 (1995) 245.
[9] R.A. Holt, A.R. Causey, N. Christodoulou, M. Griffiths, E.T.C. Ho, C.H. Woo, ASTM STP1295, American Society for Testing and Materials, West Comshohocken, 1996, p. 623.
[10] R.A. Holt, A.R. Causey, M. Griifiths, E.T.C. Ho, ASTM STP 1354, American Society for Testing and Materials, West Comshohocken, 2000, p. 86.
[11] C.N. Tomé, N. Christodoulou, Philos. Mag. A 80 (2000) 1407.
[12] G.J. Field, J. Nucl. Mater. 159 (1988) 3.
[13] L.K.H. Leung, J.S. Jun, G.R. Dimmick, D.E. Bullock, W.W.R. Inch, H.C. Suk, Proceedings of the 7th International Conference on CANDU Fuel, Kingston, Ontario, Canada, 2001 September.
[14] C.E. Ells, E.F. Ibrahim, A.R. Causey, Proceedings of the International Conference on Creep, JSME/IMechEASME/ASTM, Tokyo, 1986, p. 59.