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Effect of fast neutron fluence on the creep anisotropy of Zr–2.5Nb tubes

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Abstract

The in-reactor behaviour of internally pressurised capsules of Zr–2.5Nb tubes is analysed in detail to separate the stress dependent component of deformation (creep). It is found by a rigorous statistical analysis that the creep rate varies with fast neutron fluence. At 555 K the axial creep rate increases while the transverse creep rate decreases with fluence. At 588 K the creep rate in both the axial and transverse directions increases with fluence. It is also shown that the creep anisotropy ratio R, i.e., the ratio of axial to transverse creep rate for a pressurised tube, varies with fluence, stress and irradiation temperature. These findings are discussed in terms of the irradiation-induced evolution in microstructure. The possible impact of the evolution of the dislocation substructure is discussed with reference to a self-consistent polycrystalline model that takes into account the crystallographic texture and the grain interaction strains present in zirconium alloys. The lower temperature creep behaviour is consistent with an increase with fast fluence of the single crystal creep compliance related to prismatic dislocation climb and glide, or a decrease in the single crystal creep compliances relating to basal and pyramidal slip. The creep behaviour at the higher irradiation temperature is more complicated, and there may be an influence of phase changes as well as dislocation structure. It appears that all three eigenvalues describing the single crystal creep behaviour depend on fast fluence.

1. Introduction

The anisotropic deformation of Zr–2.5Nb pressure tubes (PTs) during service in CANDU reactors [1–3] is related to the anisotropic physical properties of the hexagonal crystal structure of zirconium and the strong crystallographic texture developed during the manufacturing process [4]. The anisotropic properties of the single crystal also contribute to the development of a complex dislocation structure [5], grain morphology and second phase distribution [4]. The in-reactor deformation of zirconium alloys is due to irradiation growth, i.e., a shape change observed under no externally applied load, and creep, both thermal and irradiation induced. The resulting strain tensor is anisotropic [3,6,7].

Several studies have attempted to relate the anisotropic deformation of the polycrystalline zirconium alloys to those of individual grains by accounting for the microstructural features, particularly the crystallographic texture [3,6–11]. The development of these models depended on the availability of experimental data from creep tests on materials with properties similar to those exhibited by PTs. Since there are no direct tests that can readily be conducted on specimens obtained from full size PT to determine the anisotropic behaviour, small tubes were produced with properties similar to those of full size PTs and irradiated in the Osiris reactor in France [12,13]. In the most recent analysis of these experiments, we treated the creep anisotropy as independent of fast neutron fluence and temperature [7,11].

Subsequent microstructural studies have shown the densities of both **a**-type and **c**-component dislocations vary with neutron fluence, and that the functional dependencies of these variations on fluence, flux and temperature are different [14–18]. As well, the edge character **c**-component

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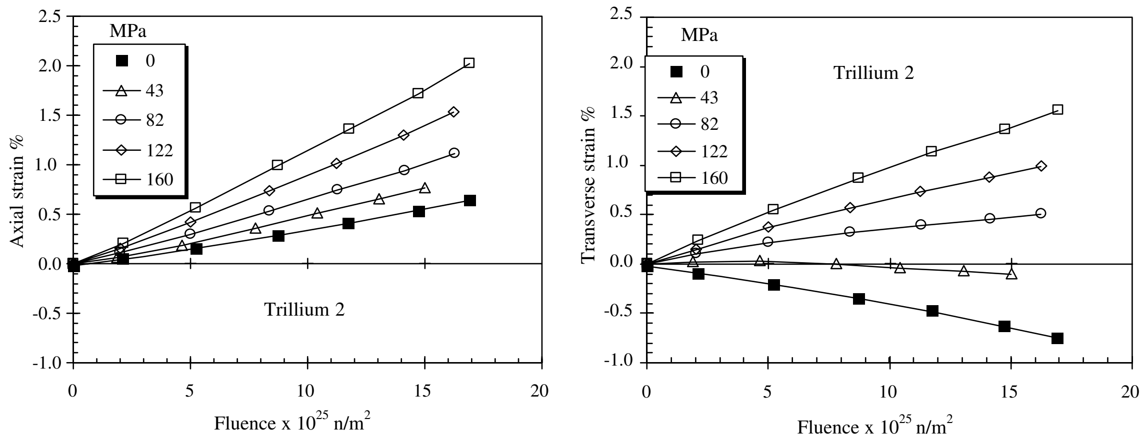

Fig. 1. Axial and transverse strain as a function of fast neutron fluence in Trillium 2 (555 K).

dislocations, initially with a Burgers vector of $1/3\langle 11\bar{2}3\rangle$ may split into two partials with Burgers vector $1/6\langle 20\bar{2}3\rangle$ [14] and those with screw character nucleate loops [16] which are likely faulted with a Burgers vector of $1/6\langle 20\bar{2}3\rangle$ or $1/2[0001]$. Crystals of different orientation contain different initial populations of dislocations [16,19]. Furthermore, the morphology and phase structure of the 'β_{Zr}'-phase, whose boundaries with the α-phase appear to be important point defect sinks [10], change continuously with time, again as a complex function of temperature and fast neutron flux [17]. Finally, radiation induces fine precipitation of β_{Nb} in the α-grains of Zr–2.5Nb [17], which might influence glide, or provide recombination sites for the radiation induced point defects. Since the irradiation creep rate is believed to be controlled by the flux of irradiation-induced point defects to the dislocations and boundaries, and the differentials in these fluxes, it is highly unlikely that either the anisotropy or the creep rates are independent of fast neutron fluence, or that the anisotropy is independent of temperature. In view of this, we have re-analysed the data (with the addition of additional data points at higher fluence) to look for fluence and temperature dependencies.

2. Analysis of experimental results

The axial and transverse creep rate of the Trillium 2 (∼555 K) and Trillium 3 (∼588 K) were evaluated for the small tubes designated as MPT in Refs. [12,13]. Five specimens were measured in each experiment. One of the five samples was unpressurised (e.g., growth specimens M03 and M04 in Refs. [12,13]). The remaining four specimens were under nominal applied transverse stresses ranging from 40 to 160 MPa and axial stresses from 20 to 80 MPa. The measured strains as a function of fast fluence (i.e., $E > 1$ MeV) are shown in Figs. 1 and 2.

To calculate the creep rate, the growth term must be subtracted from the total strain. As is evident from Figs. 1 and 2, the growth samples were measured at somewhat different accumulated fluence than the pressurised capsules and therefore the growth term must be estimated by interpolation. A spline was used to fit the growth data and then the interpolated growth value was subtracted from the total strain.

It is advantageous to find a continuous function that describes the dependence of creep strain on fluence because it provides an analytical solution for the creep rate (as a

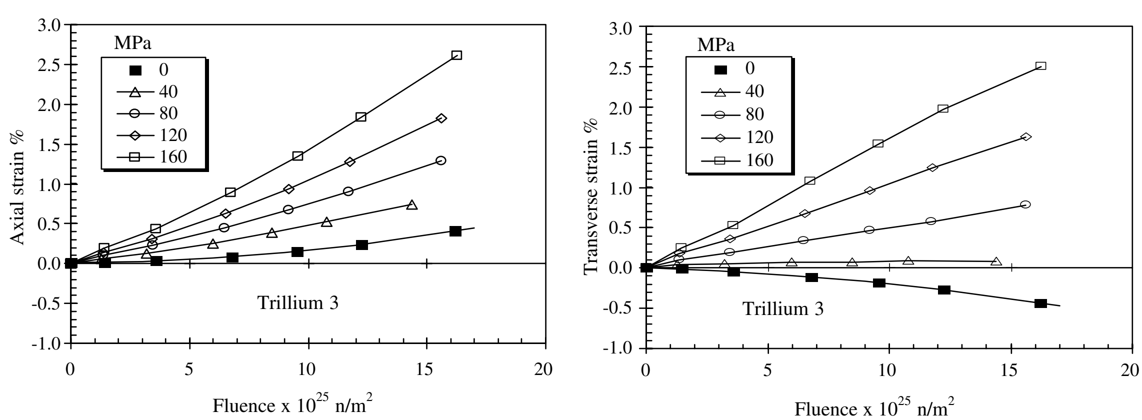

Fig. 2. Axial and transverse strain as a function of fast neutron fluence in Trillium 3 (588 K).