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Manufacturing variability and deformation for Zr-2.5Nb pressure tubes

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ABSTRACT

A research program (Task Group 3) aimed at determining the effect of microstructure variables on pressure tube performance was initiated over 30 years ago. Zr-2.5Nb pressure tubes were produced from the same ingot material by three variants on the standard CANDU reactor manufacturing process, designated by reference to routes 1, 2 and 3. Of the three Task Group 3 fabrication routes the route 1 tubes showed the largest difference compared to routes 2 and 3 and also compared with standard pressure tubes. They exhibited lower axial elongation and higher peak diametral strain. In addition, the deformation of tubes extruded by a single tube manufacturer using billets/ingots from three different producers has been studied. The results indicate that the Fe-content of the tubes has a significant effect on the final microstructure and this, in turn affects the axial elongation rates.

1. Introduction

The pressure tubes used in a CANDU[1] reactor are made from Zr-2.5Nb. The tubes are fabricated by a two-stage forging process to convert cast ingots that are approximately 3500 mm long × 580 mm diameter into two logs that are approximately 2800 mm long × 210 mm diameter. These logs are then machined to produce hollow billets that are approximately 560 mm long × 195 mm diameter suitable for extrusion. The logs are extruded at 815 °C and cold worked 27% to produce tubes that are approximately 112 mm OD and 104 mm ID. These tubes are stress relieved at 400 °C for a minimum of 24 h prior to installation in a CANDU reactor. During service these pressure tubes operate at temperatures between about 250 and 310 °C, and at coolant pressures of about 10 MPa corresponding to hoop stresses of about 130 MPa. The maximum flux of fast neutrons from the fuel is about $4 \times 10^{17}\ \mathrm{n\,m^{-2}\,s^{-1}}$. The performance of the pressure tubes during operation is a function of the fabrication history of the tubes and the operating conditions, both of which vary.

For a given set of operating conditions there is considerable variability in the deformation behaviour of pressure tubes that can be related to variations in the as-fabricated microstructure [1]. Texture and grain thickness can affect both the anisotropy and magnitude of deformation strain. In general, pressure tubes that have a higher radial basal texture parameter or Kearns factor (f_R), and have grains that are thinner in the radial direction, tend to exhibit higher diametral strain and lower axial elongation rates compared with the average. These same microstructural variables affect the deformation behaviour along a given tube because of a gradual change in grain structure and crystallographic texture from one end of the tube to the other. The net effect is that pressure tubes tend to deform at a faster rate (diametrally) when the back-end of the tube (i.e. the end leaving the extrusion press last) is installed at the fuel-channel outlet. The primary cause of the difference in microstructure along a given tube is the temperature change during the extrusion process. This end-to-end variation itself varies from tube-to-tube, due to variations in extrusion conditions from one extrusion run to the next, and also due to variations in ingot chemistry and billet processing.

The diametral expansion and axial elongation rates of pressure tubes in CANDU reactors due to irradiation deformation are important properties that limit the useful life of the reactor and the maximum power level for reactor operation. The deformation rates are a direct function of the microstructure (for example, crystallographic texture and grain size) and operating conditions (stress, temperature and neutron flux), but are also indirectly dependent on the operating conditions because of the modifying effects of the irradiation on the microstructure [1]. Therefore the in-reactor deformation behaviour of pressure tubes is controlled both by the as-fabricated microstructure and the microstructure that evolves during irradiation. Over many years data has been accumulated concerning the in-reactor deformation behaviour of pressure tubes in CANDU reactors. There are two main factors that control the in-reactor performance: (i) manufacturing variables, and (ii) ingot source. In this paper we will focus on the deformation data accumulated for tubes where the manufacturing routes have been deliberately varied to examine manufacturing variables, and where the ingot supplier has been varied to examine the 'ingot effect'.

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2. Results and discussion

2.1. Manufacturing variables

A research program (Task Group 3) aimed at determining the effect of microstructure variables on pressure tube performance was initiated over 30 years ago [2]. Zr-2.5Nb pressure tubes were produced from the same ingot material by three variants on the standard CANDU reactor manufacturing process, designated by reference to routes 1, 2 and 3, Fig. 1. The chemical specification for the source material for routes 1, 2 and 3 was varied slightly compared with the standard specification at that time [2]. The oxygen and niobium concentrations were increased slightly (oxygen increased from a mid-range of 1150–1400 ppm and niobium increased from a mid-range of 2.6–2.75 wt%) in order to maintain a high strength for the cases where the dislocation density was reduced or grain size increased.

The different manufacturing routes produced a variation in final microstructures. Table 1 shows the grain structures and aspect ratios (length:thickness). Although the location along the tube is not specified it appears as though the data refer to the front-end, i.e. the section exiting the extrusion press first. Table 2 shows the dislocation densities from the front and back-ends. Table 3 shows the Kearns' texture parameters from the front and back-ends. Tubes made by all three routes had slightly higher radial basal texture parameters relative to the standard CANDU Zr-2.5Nb pressure tubes. In addition: route 1 tubes had lower dislocation density and thinner grains and an aspect ratio (AR) of approximately 20; route 2 tubes had a similar dislocation density and grain thickness with an AR of approximately 10; route 3 tubes had a lower dislocation density and thicker grains and a grain AR of approximately 10.

Three tubes from each of the three routes were installed in a CANDU reactor and their dimensional performance has been monitored relative to standard pressure tubes. Of the three Task Group 3 fabrication routes the route 1 tubes showed the largest difference compared to routes 2 and routes 3 and also compared with standard pressure tubes. They exhibited lower axial elongation and higher peak diametral strains, Fig. 2. Previous analyses [1] showed diametral strain was strongly dependent on both basal texture and grain thickness (thinner grains and higher radial basal texture parameters corresponding with higher diametral strain rates). Based on the data presented in [2], reproduced in Tables 1–3, the two main factors that can account for the high diametral strain of route 1 material are thin grains and high radial basal texture parameters [1].

Also illustrated in Fig. 2 are data from tubes fabricated by the standard manufacturing route but from 100% recycled material. There is a statistically significant difference in the behaviour of the tubes made from 100% recycled material (quadruple-melted) compared with tubes made from <100% recycled material. This

Table 1
Measurements of grain width in the radial direction, aspect ratio (length/thickness), [2]

Route	Alpha grain width (μm)	Aspect ratio length/thickness
1	0.25	15–20
2	0.34	5–10
3	0.37	5–10
Current	0.34	15–20

Table 2
Measurements of dislocation density (10^{14} m^{-2}) on pressure tubes, [2]

	Front	Back
Route 1	2.6	3
Route 2	6	5.4
Route 3	3.3	3.2
Current	5.0–7.0	5.0–7.0

Table 3
Kearns' basal texture parameters for pressure tubes in principal tube directions, [2]

	Front			Back		
	f_R	f_T	f_L	f_R	f_T	f_L
Route 1	0.39	0.58	0.04	0.4	0.57	0.03
Route 2	0.35	0.6	0.04	0.39	0.57	0.04
Route 3	0.36	0.6	0.04	0.36	0.6	0.03
Current	0.3	0.63	0.08	0.34	0.6	0.05

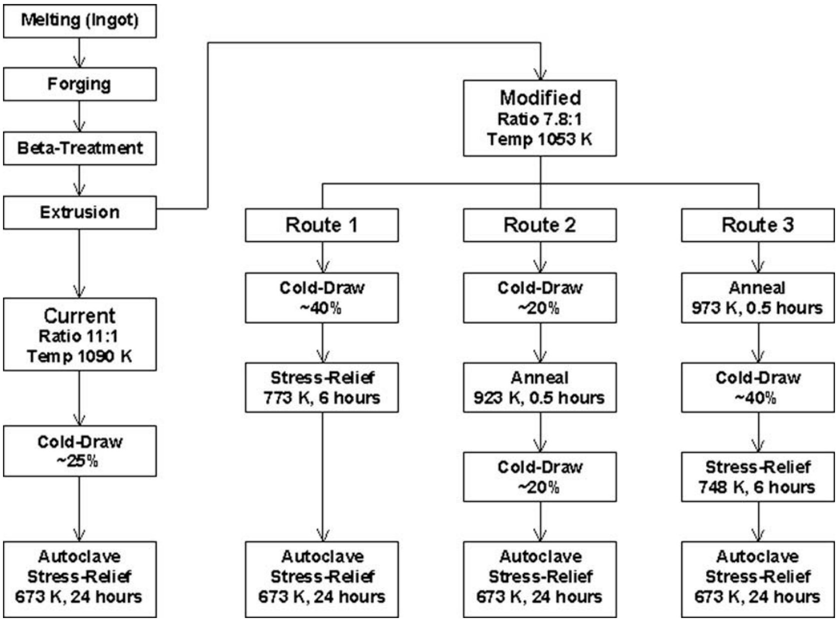

Fig. 1. Manufacturing routes for cold-worked Zr-2.5Nb pressure tubes [2].

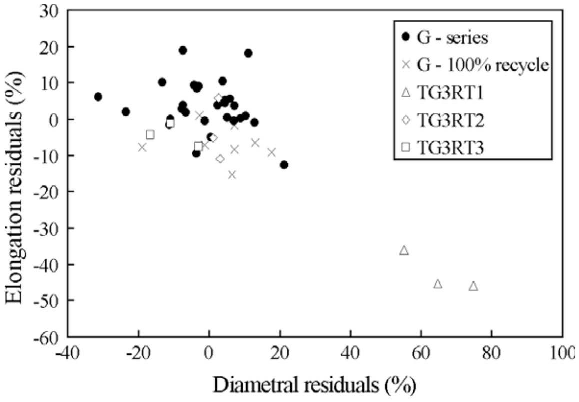

Fig. 2. Relative axial and diametral strain for cold-worked Zr-2.5Nb pressure tubes at a single station.

behaviour is one example of the so-called 'ingot effect'; groups of tubes produced from particular ingots can behave differently even though they were produced by nominally the same tube manufacturing process. In this case, tubes differentiated by ingot processing, can be identified as having distinct deformation characteristics.

2.2. Ingot-source variables

In many cases the deformation behaviour of the pressure tubes can be associated with the ingot from which they were manufactured. For tubes manufactured from the same ingot by the standard route (Fig. 1), their deformation behaviour may be subclassified according to other manufacturing variables such as extrusion temperatures, pressures and pre-extrusion soak-times. This 'ingot effect' is readily apparent from an examination of axial elongation data. Figs. 3 and 4 show the axial elongation of groups of pressure tubes from different ingots in two CANDU reactors (A and B).

The cause of this difference in behaviour is often not readily apparent based on the known manufacturing variables. Although the variation in the deformation behaviour can often be related to differences in the final microstructure for these different groups of tubes, there is no simple explanation to account for the final microstructure based on known manufacturing variables (beta-quenching of billets, soak-times, extrusion pressures, stress-relief duration). Previous reports had identified that Fe-content was a variable that correlated with the axial elongation of these pressure tubes for these reactors [3]. This apparent dependence on Fe-content is illustrated for reactor A in Fig. 5, and reactor B in Fig. 6. A microstructural examination of the tubes shows that the Fe may be a surrogate for microstructural parameters that correlate with

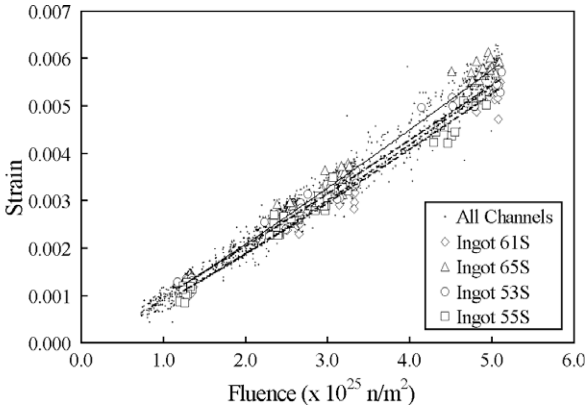

Fig. 3. Axial elongation of pressure tubes in a CANDU reactor (A) showing the variability associated with tubes from different ingots.

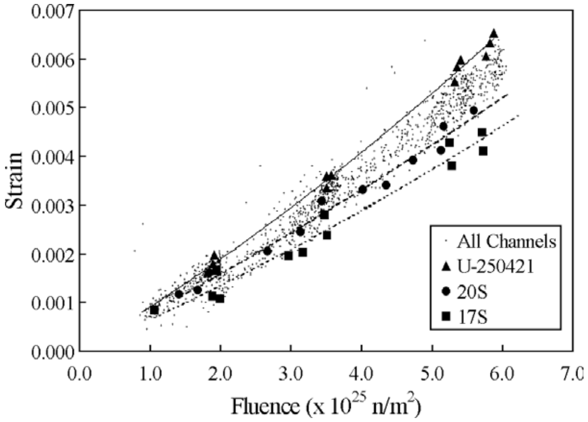

Fig. 4. Axial elongation of pressure tubes in a CANDU reactor (B) showing the variability associated with tubes from different ingots.

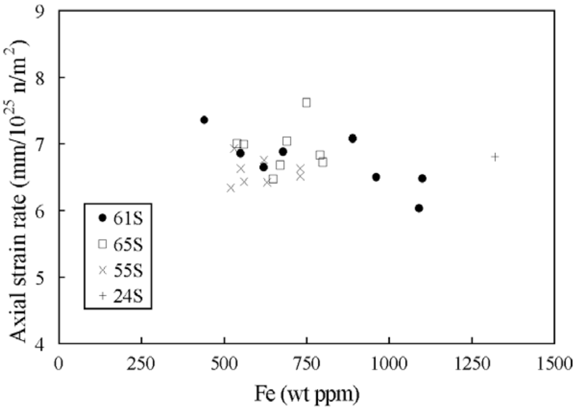

Fig. 5. Axial elongation rates of pressure tubes in a CANDU reactor (A) showing the relationship with Fe-content from tube offcut analyses (ingots 61S, 65S, 55S and 24S).

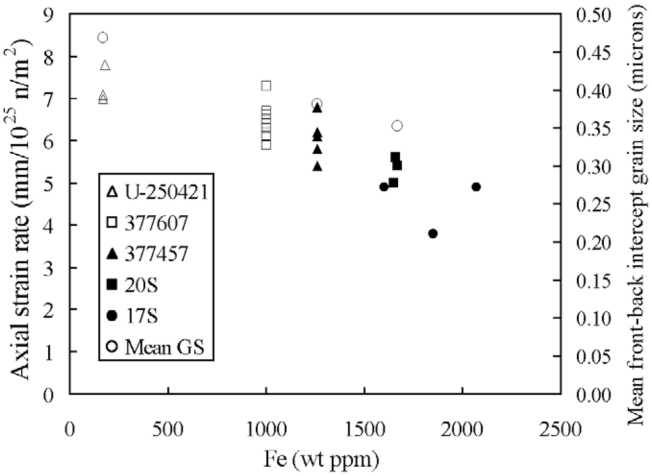

Fig. 6. Axial elongation rates and mean front and back-end grain sizes for pressure tubes in a CANDU reactor (B) showing the relationship with Fe-content from ingot analyses (ingots 377607 and 377457) and tube offcut analyses (ingots U-250421, 20S and 17S).

Table 4
Grain thickness and Kearns' texture parameters for principal tube directions

Ingot	Tube	Front GS	Back GS	Front f_L	Back f_L	Front f_R	Back f_R	Fe	Axial strain rate
U-250421	A	0.339	0.265	0.048	0.039	0.324	0.384	170	7.56
U-250421	B	0.45	0.457	0.054	0.047	0.331	0.356	170	7.66
U-250421	C	0.391	0.33	0.051	0.044	0.319	0.355	180	8.48
17S	CC	0.276	0.272	0.14	0.057	0.331	0.344	1850	4.09
20S	EE	0.404	0.245	0.087	0.06	0.296	0.347	1670	5.8
20S	FF	0.509	0.233	0.069	0.065	0.271	0.332	1660	6.05
17S	AA	0.302	0.292	0.136	0.055	0.355	0.341	2070	5.26
17S	BB	0.279	0.276	0.164	0.063	0.384	0.362	1600	5.33
20S	DD	0.457	0.237	0.066	0.065	0.277	0.347	1650	5.43

Table 5
Correlation coefficients for grain thickness and Kearns' texture parameters for principal tube directions

	Front GS	Back GS	Front f_L	Back f_L	Front f_R	Back f_R	Fe	Strain rate
Front GS	1							
Back GS	0.08	1						
Front FL	−0.74	−0.23	1					
Back FL	0.18	−0.53	0.48	1				
Front FR	−0.82	0.34	0.67	−0.23	1			
Back FR	−0.34	0.19	−0.23	−0.69	0.38	1		
Fe	−0.21	−0.61	0.71	0.85	−0.02	−0.68	1	
Axial strain rate	0.38	0.53	**−0.77**	**−0.75**	−0.10	0.49	**−0.92**	1

the Fe-content, i.e. texture and grain size. To illustrate this, the mean intercept grain sizes (radial direction) for three selected tubes are also shown in Fig. 6. The intercept values for grain sizes along a given direction are one way to characterize grain structure. Another method is to measure the minor axis dimension or grain thickness. Data showing grain thicknesses together with texture data are given in Table 4.

The corresponding correlation coefficients are shown in Table 5. It is evident that although there is a strong correlation between axial strain rate and Fe-content there is also a strong correlation with the axial basal texture parameter. As the microstructure is developed during the tube fabrication process there is a clear dependence on the ingot source. In this instance the ingot source/producer appears to be less significant than the effect of impurity content in the tubes, Fig. 7.

The microstructure, and not Fe-content as such, is likely to be the cause of the variation in axial elongation rates. There is a clear correlation between the final microstructure and the Fe-content in many cases but further work is required to determine whether other manufacturing variables (collinear with Fe) are responsible. Apart from the variability in manufacturing processes, such as extrusion temperature and pre-heat time, that affect the microstructure developed during extrusion, one has to consider that Fe in sufficient concentrations is capable of having a modifying effect on the microstructure evolution, probably by the effect on stabilizing the β-phase during the extrusion process. By the same token it is likely that oxygen, being an α-stabilizer and a significant impurity/alloying element, may have an opposite (but weaker) effect [1]. Oxygen may also be significant in its effect on the intrinsic properties of the α-phase, for example by increasing hardness. However, there is no definitive correlation between oxygen and axial elongation and only a multi-variable statistical analysis, taking into account the correlation between all the variables, can reveal the primary explanatory variables.

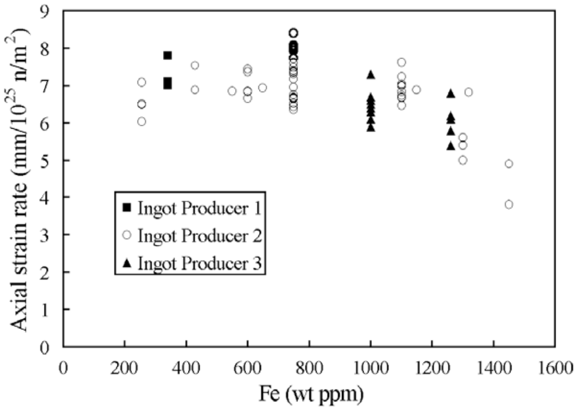

Fig. 7. Axial elongation rates for pressure tubes in two CANDU reactors (A and B) showing the dependence of Fe-content.

3. Conclusions

Manufacturing parameters control microstructure and therefore the in-reactor deformation behaviour of Zr-2.5Nb pressure tubes. There are cases where manufacturing variables are relatively fixed, i.e. a standard route is followed, and the pressure tubes still exhibit significantly different deformation behaviour. In such cases the material source (ingot) appears to be important. One factor that can be related to the ingot source is the impurity content. Although the behaviour of the pressure tubes is ultimately related to the final microstructure there are indications that the microstructure (and therefore deformation behaviour) is related to the level of impurities when they vary significantly.

Both the ingot properties and the tube manufacturing process affect the axial elongation of pressure tubes. Gaining control of the ingot effect and maintaining control of the tube fabrication process should ensure a significant reduction in tube-to-tube variability in deformation.

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