IMPROVED ZR-2.5NB PRESSURE TUBING FOR FUTURE HW REACTORS

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Abstract

The diametral expansion of pressure tubes in CANDU reactors due to irradiation creep is an important parameter that affects the critical-heat-flux and is therefore a reactor life-limiting property. There is considerable variability in diametral strain rates between tubes in different reactors that can be associated with manufacturing practice and their microstructure. As aging reactors are being refurbished and fuel channels are being replaced there is an opportunity to take advantage of our prior experience and select manufacturing parameters that lead to optimised pressure tube performance. Statistical analysis has been used to assess the diametral creep performance as a function of manufacturing variables and microstructure parameters.

1. Introduction

The pressure tubes designed for use in CANDU heavy water reactors are made from Zr-2.5Nb. The tubes are fabricated by a two-stage forging process to convert cast ingots into logs that are then hollowed to produce billets suitable for extrusion. The billets are extruded in the $(\alpha+\beta)$–phase and cold worked to produce tubes that are approximately 6 metres long with an 112 mm outer diameter and 104 mm inner diameter. These tubes are stress-relieved prior to installation in a CANDU reactor. During service these pressure tubes operate with coolant temperatures between about 250°C and 310°C, and at coolant pressures of about 11 MPa corresponding to hoop stresses in the tubes of about 130 MPa. The maximum flux of fast neutrons in the pressure tubes from the fuel is about 4×10^{17} $n\cdot m^{-2}\cdot s^{-1}$. The performance of the pressure tubes during operation is a function of the microstructure of the tubes (dictated by fabrication history) and the operating conditions, both of which vary.

For a given set of operating conditions there is considerable variability in deformation behaviour of pressure tubes that can be related to variations in the as-fabricated microstructure [1–3]. Zirconium alloys have a built-in anisotropy (directional dependence) due to their hexagonal close packed lattice structure. Alignment of this lattice structure occurs during material fabrication. 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 [4], and have grains that are thinner in the radial direction tend to exhibit higher diametral strain and lower elongation rates compared with the average [2–3]. Grain boundaries are sinks that capture and hold migrating radiation induced defects such as vacancies and interstitials. 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 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 elongation rates of pressure tubes in CANDU reactors due to irradiation damage are important properties that limit the useful life of the reactor and the maximum power level for reactor operation. Diametral expansion, in particular, is the main life-limiting factor for CANDU reactors. Future Heavy Water Reactors will benefit from improved deformation performance. 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 [5-7]. Therefore, the in-reactor deformation behaviour of pressure tubes is controlled both by the as-fabricated microstructure and the microstructure that evolves during irradiation.

The population of in-service pressure tubes that have undergone inspection and diametral gauging provides a rich source of information regarding the deformation of pressure tubes as a function of operating conditions and material properties (microstructure). Not only is there natural variability throughout the population of in-service pressure tubes, the manufacturing process was altered frequently (sometimes with major process changes) throughout the history of pressure tube production so that information relating the effect of manufacturing practices on deformation performance is available from an analysis of the performance of in-service pressure tubes. In addition, accelerated irradiation experiments in test reactors [8] have been completed to explore some of the known, or suspected, variables in a controlled experimental fashion. Some of the observations relating the deformation to the microstructure from both the in-service inspections and test reactor experiments are the subject of this paper. In particular, the effects of texture, grain size and dislocation density on diametral strain are presented.

2. Axial variation of diametral strain

As a result of the extrusion process, the microstructure is known to vary systematically from the front-end (extruded first) to the back-end (extruded last) of the pressure tube. The front-end exhibits coarser grain size and lower radial texture than the back-end. Early work [2-3] showed that coarser grains and lower radial texture would result in lower diametral strain suggesting that the tube front-ends would strain less than the back-ends. This led to a recent design decision to install pressure tubes with their front-ends at the region with the more severe operating conditions (i.e., the higher temperature outlet). Early reactors had pressure tubes installed with the front-end at the inlet (BEO installation) and the latest reactors have tubes installed with the front-end at the outlet (BEI installation).

Figure 1 shows the diametral strain exhibited at the axial midline for pressure tubes in two CANDU 6 reactors. Although one of these reactors has BEO pressure tube installation and the other has BEI pressure tube installation, this comparison at the axial midline of the tube is independent of the pressure tube orientation. The plotted strains are commensurate because this data is selected from fuel channels that have nearly identical operating conditions at the axial midline of the tube. All else then being equal, the diametral strain for these two sets of pressure tubes in these two reactors are not distinguishable.

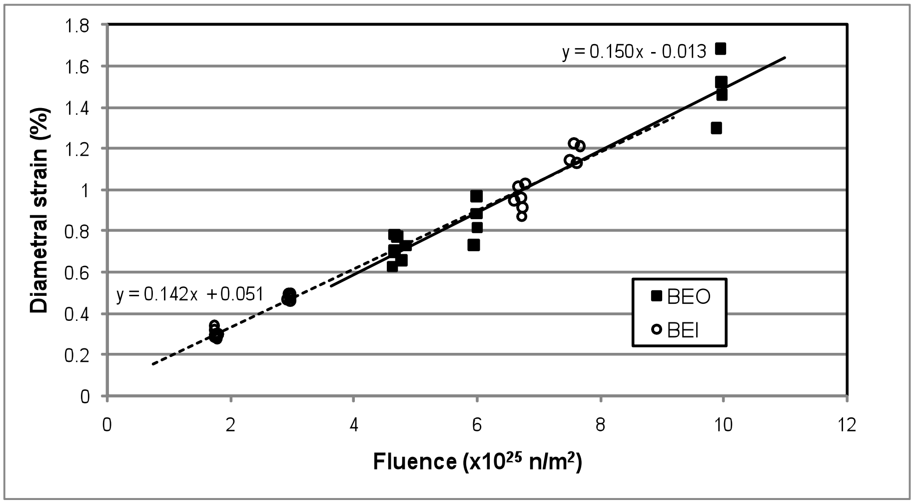

Figure 1. Diametral strain at axial midline of tube for pressure tubes in two reactors; one unit installed with tube back-end at outlet (BEO) and one unit installed with tube back-end at inlet (BEI).

Figure 2 shows the diametral strain for pressure tubes in the same reactors, under nearly identical operating conditions, at the inlet. The back-end (BEI orientation) has higher diametral strain than the front-end (BEO-orientation). Similarly, at the outlet, Figure 3 shows the back-end (BEO orientation) has higher diametral strain than the front-end (BEI orientation). Since, this comparison has been careful to control for operating conditions and potential differences between the two reactors, the cause of the different diametral strain behaviour between the front-end and back-end is attributed to the material properties – namely the microstructure (texture and grain size). The results clearly illustrate that, for this dataset at least, the back-ends of the pressure tubes exhibit higher diametral strain than the front-ends.

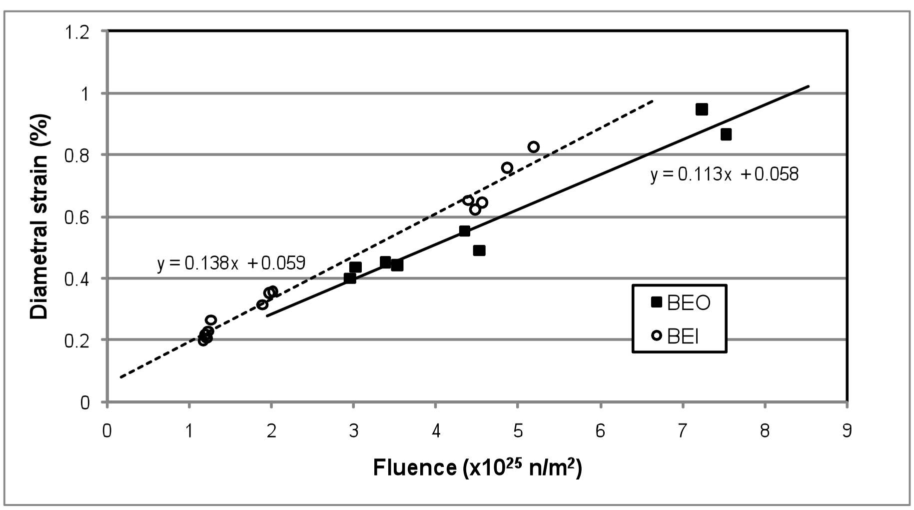

Figure 2. Diametral strain near inlet for pressure tubes in two CANDU reactors (same tubes as Figure 1); one unit installed with tube front-end at inlet (BEO) and one unit installed with tube back-end at inlet (BEI).

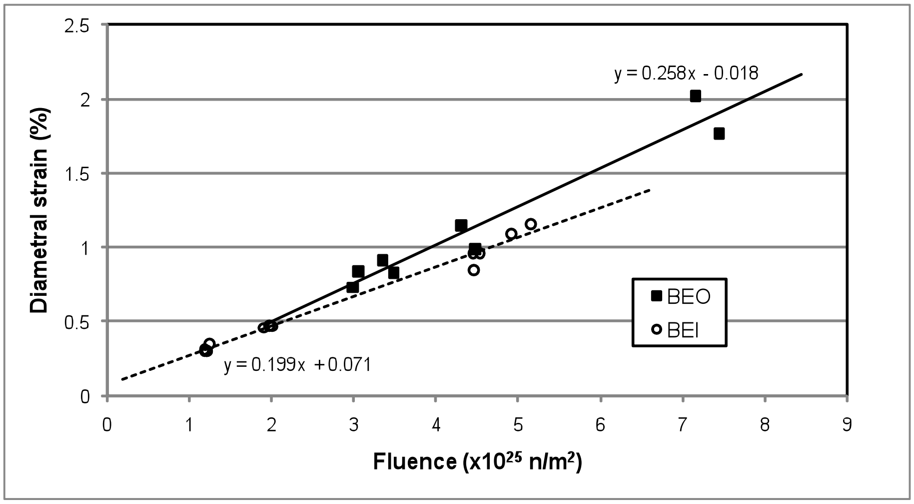

Figure 3. Diametral strain near outlet for pressure tubes in two CANDU reactors (same tubes as Figure 1 and 2); one unit installed with tube back-end at outlet (BEO) and one unit installed with tube front-end at outlet (BEI).

3. Modelling the dependence on texture and grain size

The as-manufactured texture has been measured for a large number of in-service pressure tubes. The radial (f_R), transverse (f_T) and longitudinal (f_L) texture parameters are available to study the relationships with texture. However, the manufacturing process of pressure tubes ensures that f_L is small which, since $f_R + f_T + f_L = 1$, means that f_R and f_T are nearly completely correlated. Either f_R, or f_T or a combination of both could be used as an attribute to establish the relationship between texture and diametral strain. We chose f_R by itself for the following analyses. The α-zirconium grains are thin platelets [9] and it is the thickness of these platelets that is chosen as the attribute to describe grain size.

Grain thickness and texture are both potential variables for predicting diametral strain. Furthermore, both of these variables are generally correlated; the front-end exhibits coarser grain size and lower radial texture than the back-end. Both variables have to be considered simultaneously when trying to understand the relationship with diametral strain. Grain thickness and texture are available for only a small number of gauged pressure tubes. In order to utilize all of this data obtained at a range of different operating conditions, a means to normalize the data to common operating conditions is required. Current deformation models (e.g., [10]) can be used to predict the mean behavior of a pressure tube under the measured operating conditions. The residual (measured/predicted) provides the deviation from the mean strain and this residual becomes a measure of the variability that is not explained by the operating conditions. This remaining variability is attributed to the material properties so that plotting the residual as a function of grain thickness and texture should provide an indication of the dependence of the diametral strain on grain thickness and texture. Figure 4 is a 3D plot of the diametral strain residual as a function of grain thickness and texture.

The data in Figure 4 can be fitted to a response surface as shown in Figure 5. The functional form and the parameters of the response surface are provided in Table 1.

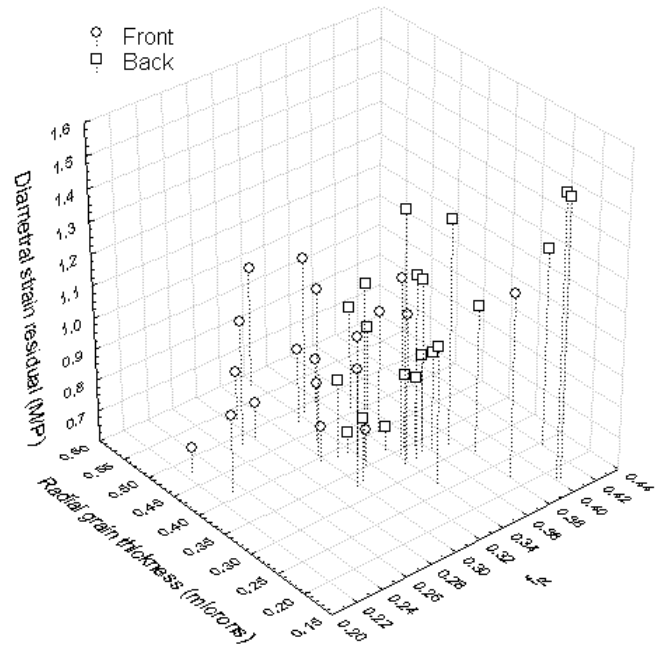

Figure 4. Diametral residuals as a function of the Kearn's radial texture parameter and the mean radial grain thickness from historical CANDU pressure tubes. Drop lines end at the texture/grain thickness plane as a visual aid to help see the 3D perspective.

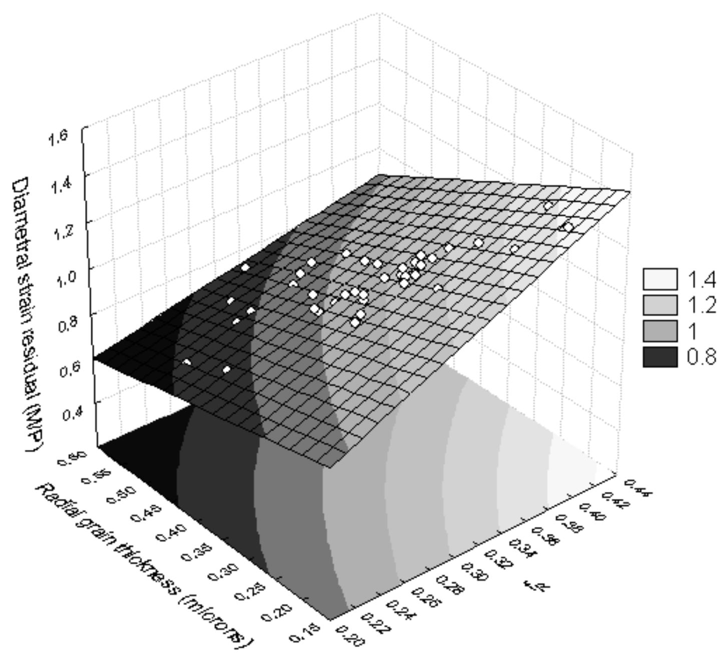

Figure 5. Diametral residuals (measured/predicted) fitted surface as a function of Kearn's radial texture parameter and the mean radial grain thickness. White dots locate the predicted value of the diametral residuals for the observed texture and grain thickness (from Figure 4). Fitted model provided in Table 1.

Table 1. Model parameter estimates of fitted surface in Figures 5.

	Parameter	Std Error	t	p	-95% cnf. Limit	95% cnf. Limit
Intercept	0.380	0.294	1.29	0.2053	-0.217	0.976
f_R	2.85	0.68	4.18	0.0002	1.47	4.23
gr.th.*f_R	-2.86	1.18	-2.42	0.0205	-5.25	-0.47

Figure 6 shows a contour plot of the model overlaid with the fitted historical CANDU 6 data. Here it can be seen that the back ends, with higher radial texture and smaller grain size, show higher diametral strain than predicted. The front ends, with lower radial texture and larger grain thickness, show lower diametral strain than predicted.

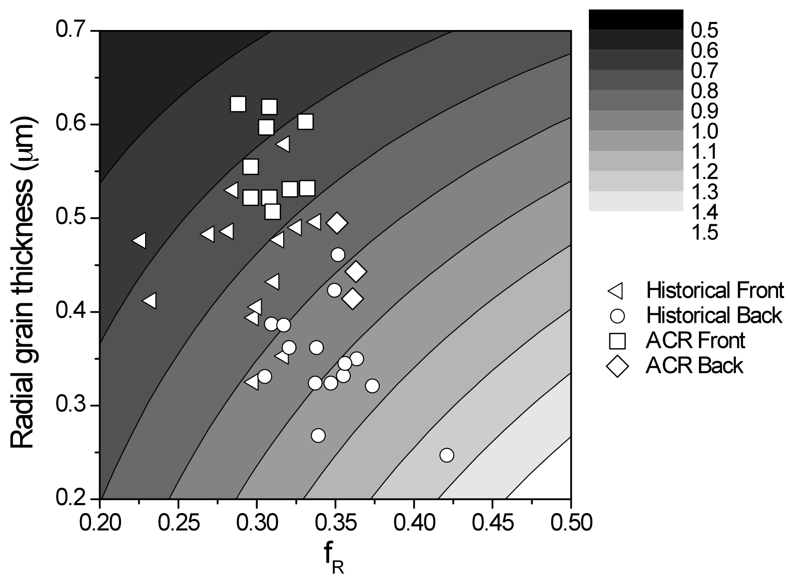

Figure 6. Contour plot of the response surface. The contour lines and gray scale indicate the diametral strain residual (M/P). Data points overlaid on the contour plot are the coordinates of the microstructure attributes for various pressure tubes. The historical data is the same as the fitted data from Figures 4 and 5.

Also overlaid on Figure 6 are the radial textures and grain thicknesses of tubes manufactured by the proposed process for future ACR pressure tubes [9]. Although both the front and back radial texture have higher than average values compared to the historical CANDU 6 tubes, the ACR tubes straddle lower isopleths of the contour plot. Therefore, lower diametral strain is predicted for the entire length of the ACR pressure tube when manufactured by this process.

4. Controlling microstructure through manufacturing

Historically, most pressure tube orders have undergone some change to the manufacturing process. Key process changes are: source material (Kroll process or electrolytic powder), number of melts for the ingot (two or four), forging sequence, β-quenched sequence, β-quench temperature, heating times before extrusion, extrusion temperature, extrusion rate, etc [3]. In many cases several process variables were changed at once making it difficult to ascertain which combination of manufacturing parameters gives a pressure tube with the lowest diametral creep. A good example of how these changes can affect the diametral creep performance is shown in Figure 7 and 8. In Figure 7, the radial texture parameter for the pressure tubes made for four recent reactor orders is shown. Based on a consideration of texture alone the tubes made with Process C would be predicted to have higher diametral strain than tubes made from the other three processes.

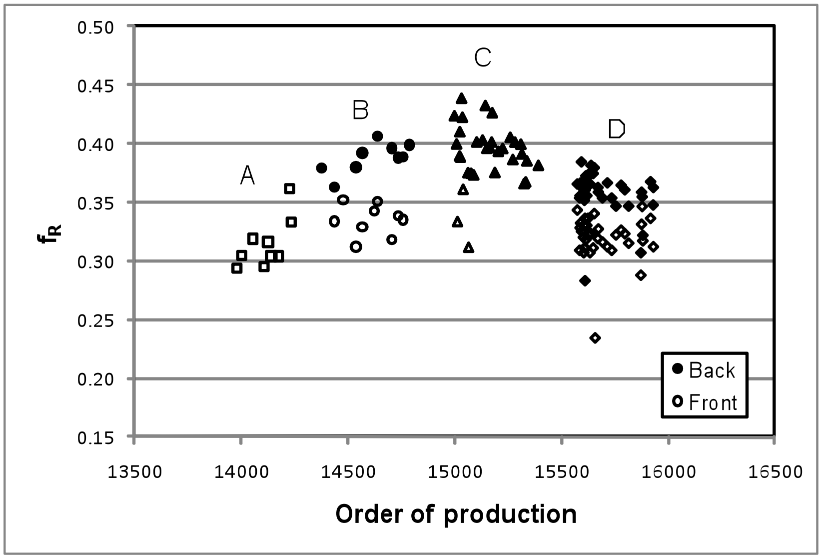

Figure 7. Radial texture parameters for the back-ends and front-ends of recent production tubes. The labels indicate different manufacturing routes.

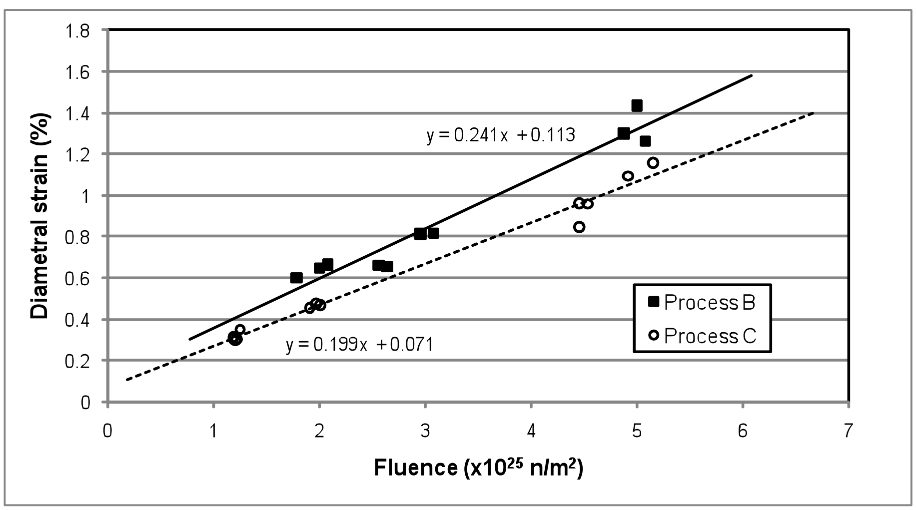

Figure 8. Diametral strain near the outlet for pressure tubes in two CANDU reactors (both installed as BEI). This figure compares diametral strain of tubes made following Process B and Process C under near identical operating conditions.

The actual diametral strain is compared for tubes manufactured by Process B and tubes manufactured by Process C in Figure 8. Clearly the Process C tubes perform better (lower strain in Figure 8) than the process B tubes in spite of the significantly higher radial texture from Process C. Again, the data in Figure 8 is selected for nearly identical operating conditions. It may be that the grain thickness of the Process C tubes is much coarser than the Process B tubes as discussed in Section 3 but grain thickness measurements are not available for Process B tubes. Regardless, predictive models must include all possible explanatory microstructure variables and be cast in a multivariate framework if sense will be made of the observations.

One other potential microstructural variable that may affect deformation is dislocation density. Micro-pressure tubes that had a four-fold change in dislocation density (from cold-working) were irradiated in the OSIRIS reactor. By normalizing for the texture and temperature variations between the test capsules the trend with varying dislocation density was assessed (Figure 9). This experiment provides no evidence that the as-manufactured dislocation density affects diametral strain.

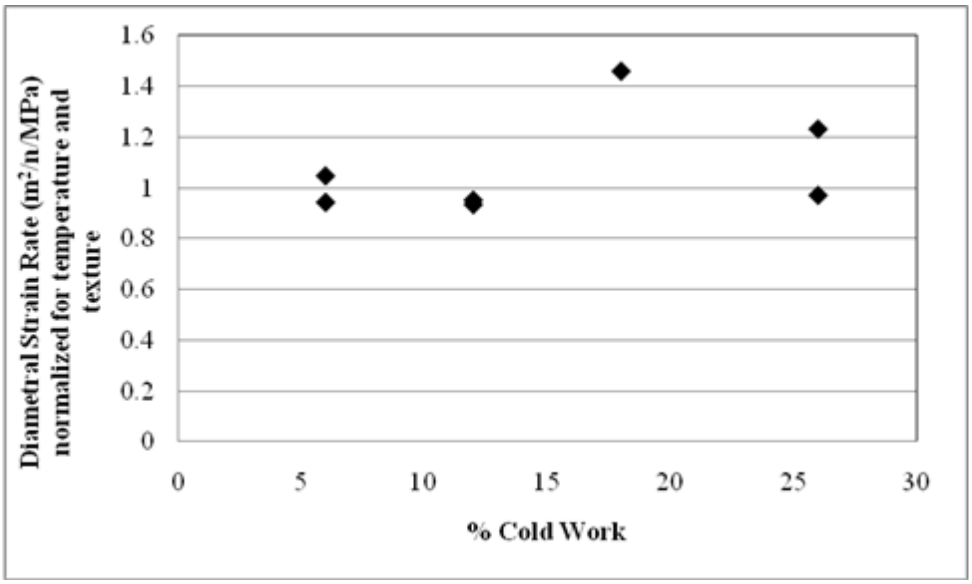

Figure 9. Trillium 5 normalized diametral strain rates showing no significant dependence on cold work.

5. Conclusions

An analysis relating the diametral creep of Zr-2.5Nb pressure tubes in operating CANDU reactors with microstructure variables is showing that the diametral creep is sensitive to both texture and grain structure. The microstructure is a function of the manufacturing variables. However, there is at present no specific combination of manufacturing variables that can be recommended to give an optimized microstructure for the purpose of generating a minimum diametral creep response. Although manufacturing routes can be identified that tend to minimize the diametral creep, simply reproducing old manufacturing methods is not the most efficient way to increase reactor lifetimes. The key to making progress is to realize that the models must be considered as multivariate and no one variable can be considered outside the context of all other known variables. Texture and grain size are thought to be the key parameters controlling the material variability and the diametral strain. Dislocation density does not appear to be an important driver of diametral strain. Work is continuing with the microstructural characterisation of many more pressure tubes to gain increasing insight and confidence in the correlations presented here in order to recommend an optimized manufacturing route for pressure tubes.

6. References

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