A Lower Bound Failure Criterion in Superplasticity of the Zr-2.5%Nb Alloy CANDU Pressure Tubes

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ABSTRACT

In a CANDU reactor the pressure tubes (Zr-2.5%Nb) form the main coolant pressure boundary within the reactor core. Consequently they are designed to forestall all anticipated operating both normal and abnormal conditions. During postulated accident scenarios, such as a loss-of-coolant accident (LOCA), the pressure tubes could be subjected to severe temperature transients while the coolant system pressure is still relatively high.

Due to the non-uniform creep deformation the pressure tube may either contact the calandria tube or it can fail locally at the hottest point by wall thinning before contact. To assess the potential for local failure a criterion in the form of a lower bound local failure criterion was developed, based on the experimental tensile testing data in temperature range (~ 850°C) where Zr-2.5%Nb alloy has a superplastic behavior. For the lower bound local failure criterion it is assumed that the pressure tube had an axial scratch at the position of maximum creep strain and failure occurred by necking to zero wall thickness at this scratch.

The developed lower bound failure criterion correlates the total elongation to fracture as function: the inhomogeneity factor, the work –hardening coefficient and the strain-rate exponent.

Comparison between analytical predictions and experimental results, for uniaxial fracture strains will be presented.

INTRODUCTION

The design of CANDU fuel channels has evolved to accommodate higher power output [1]. All channels have had the same basic design, which is illustrated in Figure 1. This figure shows the four key components for each of the few hundred horizontal fuel channels in a typical CANDU reactor core. These components are: a pressure tube, a calandria tube, end-fittings and annulus spacers. The main functions of these pressure tubes, which are the major component of each fuel channel assembly, are to support and locate the fuel in the reactor core and allow the pressurized heavy primary coolant to be pumped through the fuel and remove its heat. Annulus spacers keep each pressure tube separated from the surrounding calandria tube and allow the cool calandria tube to provide a sag support for the hot pressure tube containing the fuel and heavy water primary coolant.

There is some postulated accident conditions for CANDU project that had been included in safety analysis, which invariably conducted at non-uniform heating of the pressure tubes. These situations can be generated under the following conditions:

- The stratifying of the cooled primary agent;
- The non-uniform heating from LOCA transients (Loss-of-Coolant-Agent);
- The localized heating of the pressure tubes (hot-spot).

Every of above mentioned situations could determine a localized deformation on the pressure tube, made from Zr-2.5%Nb alloy. Thus, is developed a thinning wall of the pressure tube that may reaches high values before contacting to surrounding calandria tube.

The temperature range between 600°C-1000° is interesting for Zr-2.5%Nb alloy. In this temperature range the mentioned zirconium alloy exhibits two coexisting phases: α-Zr and β-Zr. This fact favors the appearance of the superplasticity phenomenon.

At high temperature it has been developed the suitable fracture criterion, in order to assess localized rupture of the pressure tubes wall. There are two possible situations:

- The developing of the uniform circumferential deformation demands the “upper limit criterion”;
- The developing of the localized deformation at hottest spot on the pressure tube wall, which overlapped with a defect presence (like as axial scratch proceeded from the fabrication routes) demands the “ lower bound limit criterion”.

The lower bound criterion is a matter of great concern closely related with behavior of the Zr-2.5%Nb in superplastic temperature range. Consistent with the uniform ballooning of the CANDU pressure tube, at 18% total elongation during LOCA transients, the rupture phenomenon is avoided because of the contact achievement with calandria tube (70°C). As regards superplastic elongation, it could reaches values higher than 18% before rupture. At 850°C for Zr-2.5%Nb we have been obtained over 150% fracture strain values.

This paper contains the investigation at high temperature of the superplastic instability on Zr-2.5%Nb alloy, phenomenon that has been influenced by the geometric inhomogeneous presence. Build upon the experimental data achieved in tensile tests one has been developed a suitable criterion for fracture strain and its predictions will be compared with similar criteria from other papers.

PLASTIC INSTABILITIES IN UNIAXIAL TENSION TESTS AND FRACTURE ELONGATION

Many authors [2], [3], [4], have investigated a class of instabilities, which could be defined as phenomena related to the locally thinning of a region or necking in a material containing defects under the performing of a tensile stress. The instability phenomena were related of the work-hardening coefficient, n and strain-rate sensitivity m. Some of criteria have been proposed in terms of different choices of variables for describing the onset instabilities. Hart [2] proposed a criterion monitoring behavior of a cross-sectional inhomogeneity δA, whereas several authors chose the behavior of a relative cross-sectional inhomogeneity $\delta\varepsilon$. The analysis of Hart [3] pointed out that the value of post-uniform elongation in the steady-state deformation of a tensile bar is strongly influenced by the magnitude of the strain-rate sensitivity, with $m \geq 0.3$ being predicted to yield especially large, even "superplastic" elongations of hundreds of percent.

We consider a tensile specimen of initial length L, prestrain ε_0 and cross-sectional area A_0, where ε_0 and A_0 vary with position along the tensile axis as defined by $\partial \varepsilon_o / \partial x$ and $\partial \ln A_o / \partial x$. The load is supposed to be uniformly distributed on any local cross-section A_0 (x). This supposition implies neglecting of the nonlinear viscous effects and local plastic incompatibilities, respectively.

At every one from the modes of testing (constant load P, constant stress σ, constant strain rate $\dot{\varepsilon}$, and constant area rate $\dot{A}$) the instantaneous strain and area are ε(x, t) and A (x, t), respectively. The plastic deformation of the materials, which have exhibited superplasticity phenomenon at high temperature, is described by the following constitutive relationship:

$$\sigma \approx \varepsilon^n \dot{\varepsilon}^m \tag{1}$$

where σ and ε denote the tensile flow stress and plastic strain, respectively. The momentary material response is characterized by de work-hardening coefficient:

$$n = \left.\frac{\partial \sigma}{\partial \varepsilon}\right|_{\varepsilon} \tag{2}$$

and the strain-rate exponent (assumed positive):

$$m = \left.\frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}}\right|_{\varepsilon} \tag{3}$$

Many studies have reported m≥0.3 values for superplastic materials [3,4,5]. Hart's criterion predicts the plastic material instability under uniaxial tensile [4] for the following condition:

$$\frac{h}{\sigma} + m < 1 \tag{4}$$

The condition (4) was used to explain the high necking resistance of superplastic materials when $h/\sigma \ll 1$. According to Eq. (4), the superplastic flow is then expected for m≥1, while m≥0.3 proved sufficient in many experiments.

Following Lin's considerations, for a specimen containing a geometric or deformation imperfection, the necking initiates when the load capacity in the imperfect region is less than that in the homogenous region.

The effects of strain-rate sensitivity m, and work-hardening n, on the fracture strain of a tensile bar containing mixed defects can be predicted [2] from equation

$$\left(\frac{\partial^2 \ln A}{\partial\varepsilon\partial x}\right)_t = \frac{1}{m}\left[(1-n)\left(\frac{\partial \ln A}{\partial x}\right)_t + n\left(\frac{d\ln A_o}{dx} + \frac{d\varepsilon_o}{dx}\right) - \left(\frac{\partial \ln P}{\partial x}\right)_t\right] \tag{5}$$

In order to proceed to an analytical result, one must assume that $\delta \ln A/\delta x$ and $\delta\varepsilon_o/\delta x$ are independent and, also, that n and m are constant. By applying Eq. (5) to the variation of $(\partial \ln A/\partial x)_t$ between the homogenous and mixed-defect regions, one can find

$$\left(\frac{\partial Y}{\partial \varepsilon}\right)_x = \frac{1}{m}\left[(1-n)Y + nY_o - \frac{\delta \ln P}{\delta x}\right] \tag{6}$$

where $Y=(\delta \ln A/\delta x)_t$ and $Y_o=\delta \ln A_o/\delta x+\delta\varepsilon_o/\delta x$.

The formal solution of Eq. (6) is

$$Y = \frac{\left[nY_o - (1-n)(\delta\varepsilon_o/\delta x)\right]}{1-n} exp\left[\frac{1-n}{m}(\varepsilon-\varepsilon_o)\right] - \frac{n}{1-n}Y_o \tag{7}$$

Considering $\varepsilon_o \approx 0$ (prestrain) and differentiating Eq.7 with respect to ε one find

$$\left(\frac{\partial Y}{\partial \varepsilon}\right)_x = \frac{nY_o}{m} exp\left(\frac{1-n}{m}\varepsilon\right) \tag{8}$$

Taking into account of the inhomogeneity factor definition we find

$$Y_o = \frac{\delta \ln A_o}{\delta x} \sim \frac{\partial A_o}{A_o} = f \tag{9}$$

where f is 'inhomogeneity factor" and for us it represents 'inhomogeneity geometric factor". An account of relationship (8) can be rearranged as function of f factor as follow

$$\frac{\left(\frac{\partial Y}{\partial \varepsilon}\right)_x}{Y_o} = \frac{n}{m} exp\left(\frac{1-n}{m}\varepsilon_f\right) = F\left(\frac{1}{f}\right) \tag{10}$$

where ε_f is fracture strain.

For the function $F\,(1/f)$ one can chose the simplest form

$$F\left(\frac{1}{f}\right) = \frac{1}{f} \tag{11}$$

Consistent with equations (10) and (11) the lower bound failure criterion that we will consider for Zr-2.5%Nb, is given in the following expression:

$$\varepsilon_f = \frac{m}{1-n} ln\left(\frac{m}{nf}\right) \tag{12}$$

Analytical predictions from equation (12) will be compared with experimental results, which have been obtained from experimental tensile tests.

With regard to fracture strain one can be mentioned Hart's criterion [3]

$$\varepsilon_f = \left(\frac{1}{f}\right)^m - 1 \quad (13)$$

and Nichols's criterion [3]

$$\varepsilon_f = \left(\frac{1}{f}\right)^{\frac{m}{1-n}} - 1 \quad (14)$$

In this context it will be done comparisons between both predictions provided from equations (13) and (14) and our experimental results, respectively.

THE SUPERPLASTICITY PHENOMENON OF THE ZR-2.5%NB ALLOY

Related to the superplasticity phenomenon a significant level of research effort has been directed to the identification of the deformation mechanisms in low and high strain rate superplastic materials [5], [7], [8]. Though several models have been proposed to explain the origin of superplasticity, none has been found capable of accurately describing both the mechanical and microstructural features of superplastic deformation.

A central theme in all these models is that grain boundary sliding (GBS) is the mechanism with the most contribution to the total strain during superplastic deformation [7]. These models relate the strain rate of the accommodation processes of GBS to the macroscopically measured superplastic strain rate.

In the last time [8], the cooperative manner of GBS during superplastic flow, which reveals itself through sliding of grain groups as an entity, has been demonstrated. Such cooperative grain boundary sliding (CGBS) has been suggested [8] to be coupled with cooperative grain boundary migration (CGBM) and cooperative grain rotation (CGR).

Recent careful investigations [5] have shown that most superplastic materials tend to form cavities during deformation, which is responsible for the premature failure of several superplastic alloys.

Presence of the superplasticity is regularly associated with metals and alloys which exhibit a fine grain microstructure (<10μm), in the temperature range where two phases coexist: one softer and the other harder. In described conditions, the deformations of the materials at high temperature, could have the following features:

- The stabile deformation, assumed as special resistance towards necking, that means high values for real deformations without fracture (ε_f >100%);
- The unstable deformation (or necking), that means a high-localized deformation and fracture at least.

The pressure tubes (Figure 1) in current CANDU reactors are made from cold worked Zr-2.5 wt % Nb [6].

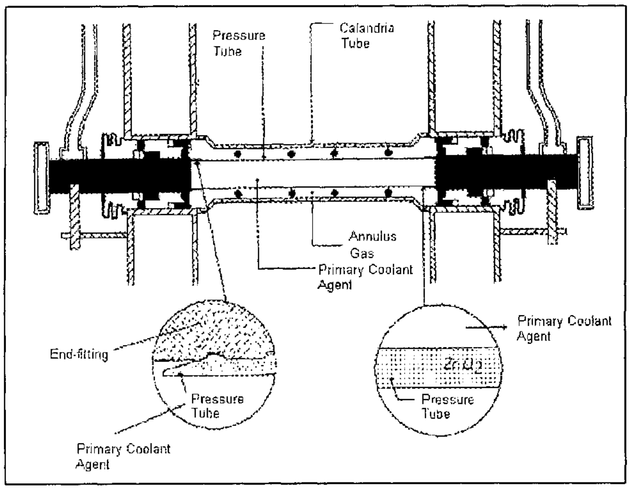

Figure1 Schematic of CANDU fuel channel assembly

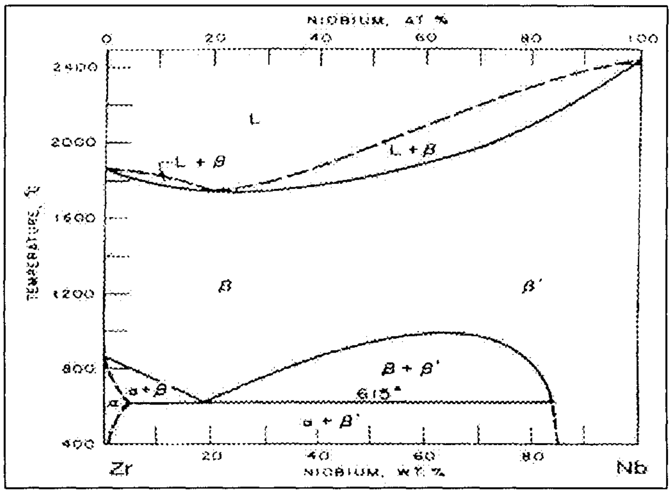

Figure 2 Zr-Nb phase diagram

The Zr-Nb phase diagram (Figure 2) showed that, on a heating process, some of microstructural changes occur and could affect the deformation modes. Thus, below 610°C the Zr-2.5%Nb tube tested is in the α-phase, over 925°C it is in β-phase, whereas between 610 °C and 925°C the alloy has two–phases structure. Along with these phase changes, recovery of cold-work begins at 600°C, the grain growth begins at 700°C and recrystallization begins at 800°C. These microstructural changes complicate the deformation modes of this alloy at high temperatures.

The CANDU pressure tubes are made from Zr-2.5%Nb by means cold-worked 40% process and this fabrication route develops a strong textured microstructure: α grains with hexagonal compact structure and basal poles within 40° angle with respect circumferential direction.

Microstructure of the CANDU pressure tubes is quite textured and contains α-Zr grains, characterized by the following dimensions: 8-20 μm on longitudinal direction, 1-3 μm on transversal direction and 0.5-1 μm on radial direction. Also, over 610°C temperature, Zr-2.5%Nb alloy is biphasic (coexists α- Zr and β-Zr phases).

All mentioned facts are bias in favor of the superplasticity presence for Zr-2.5%Nb alloy at temperature over 610°C.

EXPERIMENTAL PROCEDURE

The tests have been grouped in two categories: first contains performed tensile tests in order to obtain specific temperature when the superplasticity is maximum for Zr-2.5%Nb alloy and to obtain the strain-rate exponent m, also. Second group contains tensile tests performed on Zr-2.5%Nb specimens with geometric inhomogeneities machined on the surface. The testing specimens (Figure 3) were cut from the transverse direction of a CANDU pressure tube. Before machining the reduced gauge length, the transverse specimens were straightened and thermal treated for elimination of the residual stresses.

Tensile tests were performed at the following temperatures: 600°C, 700°C, 800°C, 850°C, 900°C and 1000°C.

The deformation rate in all these tests was $5.5 \cdot 10^{-4} s^{-1}$.

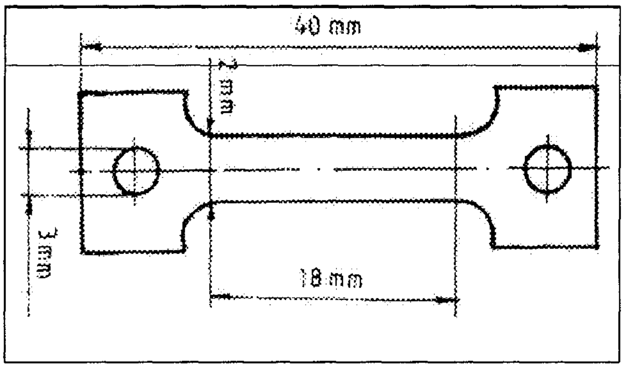

Figure 3 Type of tensile specimens cut from Zr-2.5%Nb

After processing of the experimental data over 100% fracture strains were obtained, when temperatures exceeding 700°C. The maxim rupture strain about 170% at 850°C was determined.

At higher temperature than 850°C deformation modes changes as function of α-Zr fraction phase in the alloy structure.

In order to determine the strain-rate exponent m at the temperature where superplasticity has crest value (850°C), four values for deformation rates from range $[5.5 \cdot 10^{-4} s^{-1} - 5.5 \cdot 10^{-3} s^{-1}]$ were used.

Values of the flow stresses, that mean stresses corresponding at 1% plastic strains, have been obtained by processing σ-ε curve diagrams. With the aid of an interpolation relationship, for the Zr-2.5%Nb pressure tube alloy, strain-rate exponent value obtained was m=0.31, with the correlation coefficient R=0.99.

The specimens utilized in order to determine of the inhomogeneity influence on the fracture strains have had the same dimensions as those from Figure 3. On the gage length surface a defect as V (with 60° angle between planes) has been machined. The depths of defects have had various values (Table 1). One must mentioned that admissible defect on the inner surface pressure tube has value of 0.075 mm. Tensile load was applied under constant deformation rate at the 850°C temperature.

Table 1 Characteristics of the Zr-2.5%Nb specimens having geometric inhomogeneities

Specimen	Specimen thickness (mm)	Defect depth (mm)	Initial inhomogeneity factor f(%)
1	1.589	0.05	3
2	1.643	0.10	6
3	1.483	0.15	10
4	1.541	0.20	13
5	1.480	0.25	17
6	1.671	0.30	18
7	1.564	0.35	22

The final deformation of the tested specimens has been measured take into account the nominal gauge length specimens of 15 mm.

DISSCUSION ON LOWER BOUND FAILURE CRITERIA

This paragraph has in view comparison between analytical predictions of the developed lower bound failure criterion (Eq. 12) and experimental results for superplastic behavior of the Zr-2.5%Nb CANDU pressure tube alloy. In addition to this, the predictions of two criteria, namely Hart's criterion (Eq.13) and Nichols's criterion, will be compared with our experimental results.

In Figure 4 there is a comparison between predictions of the failure strains (total elongations to fracture) given by Eq.12 and experimental results. In Eq.12 we used to the following values for the constants: strain-rate exponent value m=0.31 and the work-hardening coefficient n=0.2.The initial size of the imperfection (f) was given in Table 1. Figure 4 shows for whole range of inhomogeneity factor values, those analytical estimates is in good accordance with the experimental results. At high inhomogeneity factor values, the predictions of this criterion are very closed to those obtained in experiments.

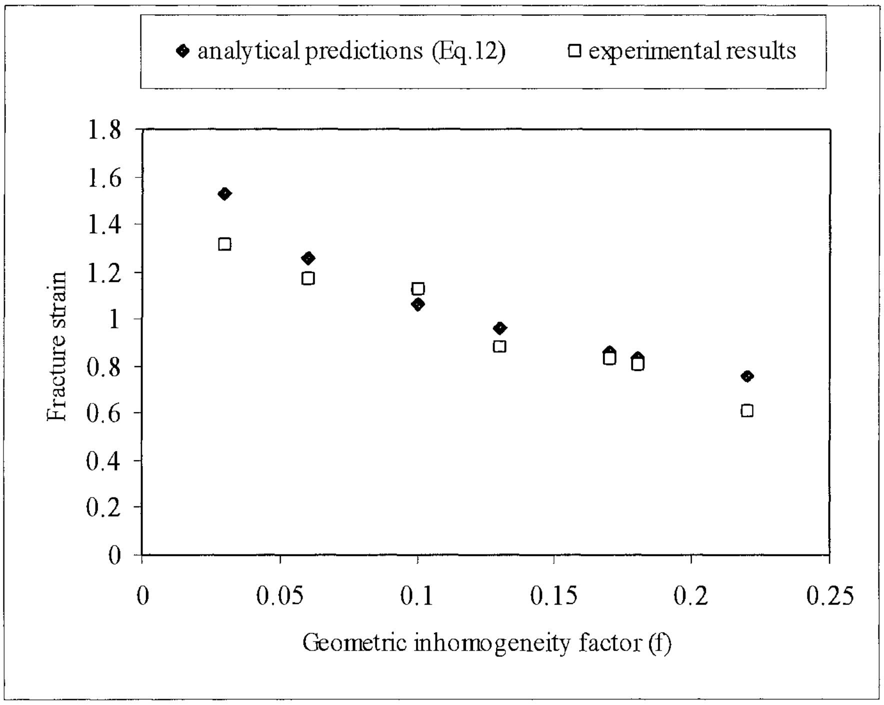

Figure 4 Comparison between analytical estimations (Eq.12) and experimental results

The estimated failure strains from Hart's criterion (Eq.13), assuming the same constant as discussed above, can be observed in Figure 5. It is clear that the lower bound failure criterion (Eq.12), as well as Hart's criterion (Eq.13) is capable of predicting the quantitative failure strain as function of initial imperfection.

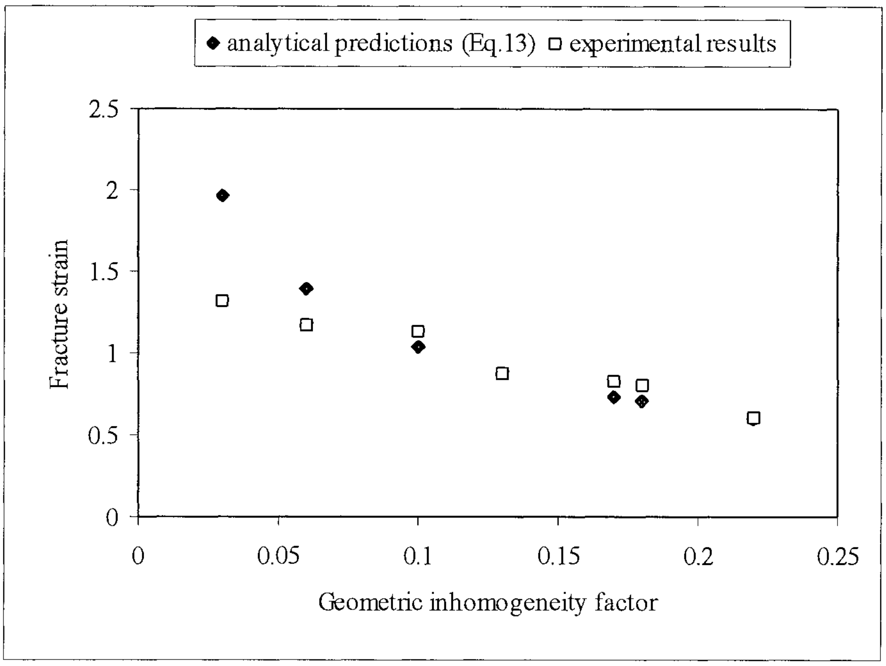

Figure 5 Comparison between analytical estimations (Eq.13) and experimental results

The Nichols's criterion (Eq.14) estimates failure strains as shown in Figure 6.

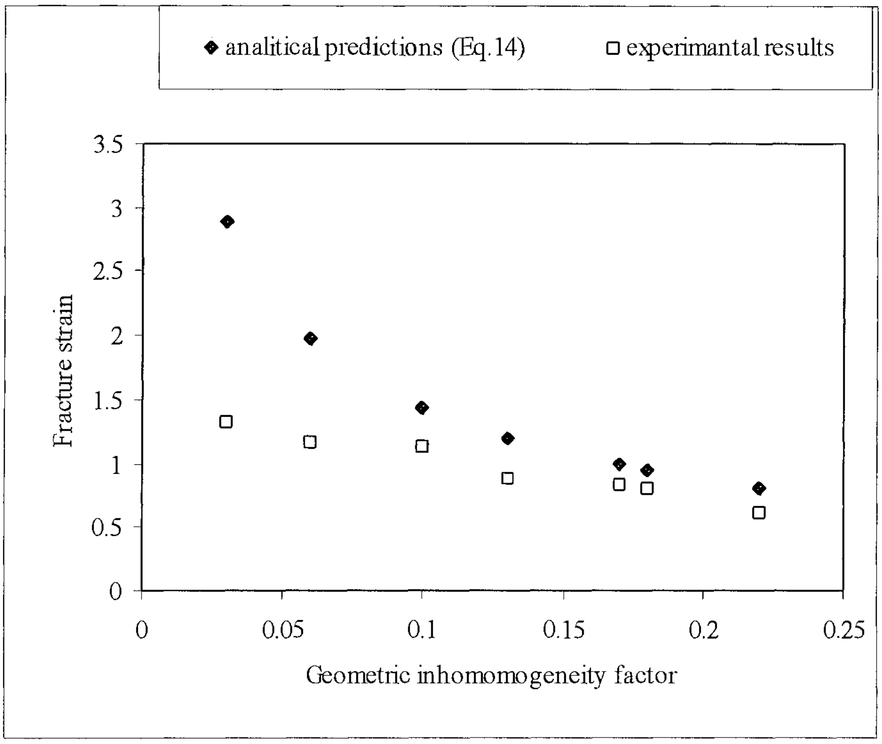

Figure 6 Comparison between analytical estimations (Eq.14) and experimental results

Compared with previous discussed criteria Eq.14 give estimations of the fracture strain with a poor confidence for Zr-2.5%Nb alloy. Thus, a questionable problem remains if one can use this criterion for the superplastic behavior of Zr-2.5%Nb alloy, assuming an initial geometric imperfection at the same values as in our experiments.

CONCLUSIONS

1. A lower bound failure criterion for Zr-2.5%Nb CANDU pressure tube alloy was established at its superplastic temperature (850°C), assuming existence of an initial geometrical inhomogeneity. This criterion has been expressed in terms of the inhomogeneity factor, strain-rate exponent and the work-hardening coefficient. The analytical predictions for the fracture strains are in good concordance with experimental data.
2. It was analyzed two criteria in the same conditions for the inhomogeneity factor: Hart's criterion and Nichols's criterion. The first covers better experimental results obtained in tensile tests at high temperature on Zr-2.5%Nb CANDU pressure tube alloy.
3. The lower bound failure criterion developed in the paper will be used in the structural analysis performed on the CANDU fuel channel components in LOCA conditions.

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