STUDY TO ASSESS THE DUCTILE FRACTURE IN ZR-2.5%NB BY J-INTEGRAL WITH THE FINITE ELEMENT METHOD USING THE GURSON-TVERGAARD-NEEDLEMAN MODEL

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Abstract

The paper describes the ductile fracture assessment of the CANDU pressure tube, Zr-25.5%Nb alloy, employing fracture mechanics parameter, *J*-integral, and based on the Gurson-Tvergaard-Needleman (GTN) model. The finite element modelling is performed with the fracture mechanics software FEACrack. The main objective is to model the behaviour of the CANDU pressure tubes (Zr-2.5%Nb alloy) for both crack initiation and its propagation through the wall thickness. The GTN model allows modelling the cracking phenomenon with the help of some specific parameters. These parameters were obtained from an iterative process for Compact Tension (CT) specimen by comparison of the experimental results with those from finite element method analyses. The extinction of the finite elements on the front of the advancing crack happens when the material cohesion achieves the critical fraction of voids. The results will improve the approach of delayed hydride cracking (DHC) in the CANDU pressure tubes using the GTN model with a finite element model.

Keywords: *J-integral, Gurson model, finite element analyses, CANDU pressure tubes*

Introduction

Due to the increase of the operating period for the nuclear reactors, the structural integrity concerns become more important, and this requires modern methods to evaluate the in-service inspection results [1]. Canadian Standard CAN/CSA Standard N285.8 [2] requests the assessment of the fracture prevention for the CANDU pressure tubes, and the Leak-Before-Break argument to be demonstrated. Fracture toughness plays an important role in the structural integrity of the pressure tubes, Zr-2.5%Nb alloy, and it should be assessed as a function of the hydrogen increase and irradiation as well.

Hydrogen concentration up-take for the normal operating condition in CANDU reactor is around 1 ppm/year, and this makes Zr-2.5%Nb to remain ductile with a hydrogen concentration of about 30 ppm, which is a target for the lifetime of the fuel channels. In this respect, the fracture toughness parameter *J*-integral is employed to describe the crack initiation and crack propagation through the pressure tube wall thickness.

A model to describe ductile fracture of metals has been suggested by Gurson [3], and his model was improved by Tveergard and Needleman, and nowadays it is known as Gurson-Tveergard-Needleman (GTN) model. The GTN model approach is based on the volume fraction of voids, which is included in the yield criterion.

The paper describes the GTN model adapted for a compact -tension (CT) specimen made of Zr-2.5%Nb alloy, which was analysed by the finite element method with FEACrack software [4]. GTN model parameters were obtained by an iterative process linked to the experimental results.

Overview of the Gurson-Tveergard-Needleman model

The ductile fracture is observed under high plastic strains or the plastic strain hysteresis [5]. The physical process in ductile fracture starts at the micro-scale and involves nucleation, growth and coalescence of micro-voids. The ductile fracture process has been modelled by using the uncoupled or the coupled models [5]. The uncoupled models suppose that the damage due to the nucleation and growth of micro-voids is insignificant and usually employ J_2 plasticity as a constitutive model. These models predict the fracture initiation upon the onset of micro-voids coalescence using a fracture criterion in the post-processing step. The coupled models can be classified into the micromechanical-based model and damage-based model, respectively.

The Gurson model [6] and further its developments [7, 8] fall in the category of micromechanical-based coupled models. Gurson proposed an approximate yield criterion and flow rules for rigid plastic porous media using an upper bound approach [6]. Tvergaard [7] studied the bifurcation on the unit cells and modified the Gurson yield criterion to account for the void interaction effects. Further, Tvergaard and Needleman [8] adjusted the Gurson model to account for the prompt loss of load-carrying capacity of the material at the onset of the microvoid coalescence. This last form of the Gurson model is mentioned as the GTN model. It is often used to model ductile fracture in metals.

For the porous materials, Gurson [6] proposed a yield potential, which was determined using cell studies with a concentric spherical void. This macroscopic yield potential for porous material was described in terms of void volume fraction (*f*), which is the ratio of the volume of the void to cell volume. The Gurson yield potential depends on the hydrostatic stress as opposed to Mises yield potential, which is independent of the hydrostatic stress. Tvergard [7] modified the Gurson model to account for microvoid interaction, and three additional void interaction parameters (q_1=1.5, q_2=1.0 and q_3=2.25) were introduced. Further, Tvergaard and Needleman [8] modified the Gurson yield criterion for the prompt loss of load-carrying capacity of the material at the onset of the microvoid coalescence. Thus, the void growth rate is accelerated after a certain void volume fraction, called the critical void volume fraction (f_c) is reached.

The plastic potential of the GTN model has the following expression [7, 8]:

$$\Phi\left(\sigma_e,\sigma_h,f^*,\sigma_y\right)=\left(\frac{\sigma_e}{\sigma_h}\right)^2+2f^*q_1\,cosh\left(q_2\frac{3\sigma_h}{2\sigma_y}\right)-1-q_3\left(f^*\right)^2 \quad (1)$$

Here: σ_e is the effective stress; σ_h is the hydrostatic stress; $\sigma_y=\sigma_y\left(\varepsilon^p\right)$ is the material hardening curve defined in terms of the effective plastic strain; f^* is the modified void volume fraction.

The accelerated void growth is initiated when the void volume fraction (f^*) exceeds the critical void volume fraction (f_c). The void growth is amplified by the accelerated void growth factor (K) until the failure void volume fraction (f_F) is reached. The initial void volume fraction (f_0) is an input parameter, and it is estimated from previous microscopic examinations.

The modified void volume fraction in the GTN model is given by:

$$f^*=\begin{cases} f, & f\le f_c \\ f_c+K\left(f-f_c\right), & f_c<f<f_F \end{cases} \quad (2)$$

Here f^* is the current void volume fraction, K is given by

$$K=\frac{\overline{f}_F-f_c}{f_F-f_c} \quad (3)$$

with

$$\overline{f}_F=q_1+\frac{\sqrt{q_1^2-q_3}}{q_3} \quad (4)$$

The change in void volume fraction is due to the growth of existing voids and the nucleation of new voids. Therefore, the rate of change in the void volume fraction f^* is expressed as a sum of the rate of growth of existing voids ($\dot{f}_G$) and the rate of void nucleation ($\dot{f}_N$). Due to mass conservation, the rate of growth of existing voids is expressed in terms of the plastic hydrostatic strain rate as:

$$\dot{f}_G=\left(1-f\right)\cdot\dot{\varepsilon}_p \quad (5)$$

The rate of the void nucleation is taken to be proportional to the effective plastic strain rate $\dot{\varepsilon}_p$ as:

$$\dot{f}_N=C\cdot\dot{\varepsilon}_p \quad (6)$$

To express the proportionally constant C a Gaussian distribution is used:

$$C=\frac{f_N}{s_N\sqrt{2\pi}}\cdot\left[-\frac{1}{2}\left(\frac{\varepsilon_p-\varepsilon_N}{s_N}\right)^2\right] \quad (7)$$

Here ε_N is the mean nucleation strain with a standard deviation s_N , and f_N is the volume fraction of nucleating voids.

After all, the GTN model has nine parameters, which can be classified into three categories:
i) q_1, q_2 and q_3 are the void interaction parameters;
ii) f_0, f_N, ε_N and s_N are the material parameters;
iii) f_c, f_F are the ductile fracture parameters.

The load-displacement curve can be divided into five stages, each of which being controlled by specific parameters. The hardening relationship $\sigma_y=\sigma_y\left(\varepsilon^p\right)$ is needed to completely describe the GTN model.

Input parameters for CT specimen geometry and FEA

To perform the finite element analyses (FEA) in the plastic domain of loading, there is a need to pay attention to the input data that should correctly describe the mechanical behaviour of the material. FEACrack software is used to evaluate crack initiation and crack propagation under plasticity assumption, and to do this it was chosen the ″porous material″ option.

Fig. 1 displays half of the CT specimen (Zr-2.5%Nb alloy), sketched in the FEACrack template, with loading setup as imposed displacement.

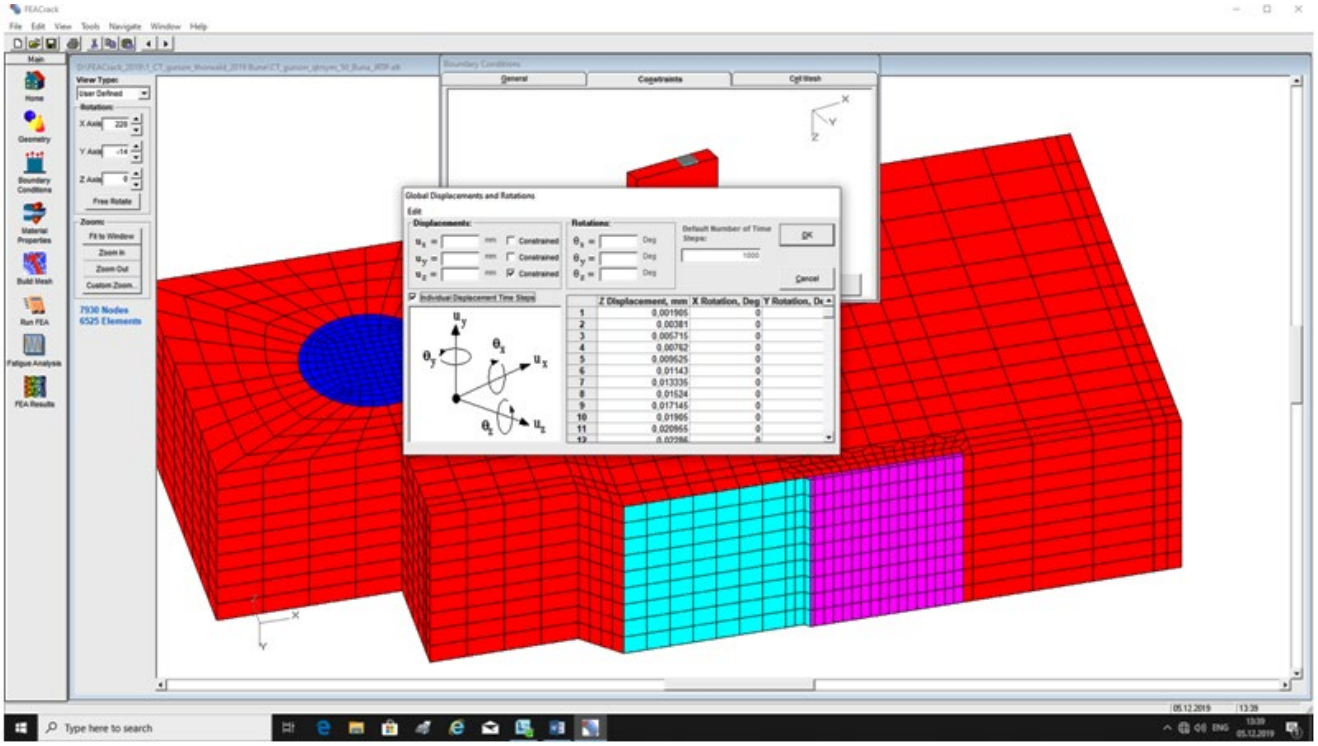


Fig. 1. . CT specimen model and mechanical loading as imposed displacement

Material properties for Zr 2.5%Nb pressure tube alloy area used in the analyses were, as follows:
- Young modulus, E = 91.7 GPa (300°C);
- Poisson coefficient, ν = 0.40;
- Yield stress, σ_y = 483 MPa;
- Ultimate tensile strength, σ_u = 487 MPa.

After some trial analyses performed with FEACrack software, the following specifications for the model are established to be used:

Program and model options:
- Analyses type: cell crack mesh for element extinction crack growth;
- Write results (stresses and strains) at element centroids;
- Use 8 node brick elements;
- Use linear kinematic element formulation (small strain).

Material model type:
- Use incremental plasticity;
- The type of plasticity is Ramberg - Osgood model;
- The number of type steps = 150 for a Δz = 2mm controlled displacement of the loading pins.

Gurson - Tvergaard - Needleman model parameters:
- void interaction parameters: q_1 = 1.29, q_2 = 0.98, q_3 = 1.664;
- initial porosity: f_0 = 0.005;
- critical porosity: f_c = 0.15;
- mean nucleation strain ε_N = 0.3, with a standard deviation s_N = 0.1, and the volume fraction of the nucleating voids f_N = 0.04.

To perform crack initiation and propagation, the model takes into account the extinction of finite elements from the crack front. The fact is performed by de-cohesion when the achievement of the critical fraction of voids in the area is reached. The extinction of the finite elements on the front of the advancing crack happens when the material cohesion achieves the critical fraction of voids.

Results

The experimental assessment of toughness of Zr-2.5% Nb, with a hydrogen concentration of 30 ppm, expressed as J_{IC} was obtained in a RATEN ICN internal R&D report [9], as J_{IC} = (35 ± 5) kJ /m^2.

From the FEACrack analyses, in the post-processing stage, at set 3 and 150th step, it is obtained the crack front shape displayed in Fig. 2 for the porosity of the elements, and in Fig. 3 the surface of the crack face, represented by killed elements, respectively.

The *J*-integral values can be seen in Fig. 4, for several steps of loading. One may see that at 150th step, the values are in domain J = 38 ÷ 40 kJ /m^2.

In the meantime, by comparing the crack surface mark from Fig. 3 with those from the experimental work, we found that they are quite similar. Therefore, and the conclusion is that the fracture toughness of Zr-2.5%Nb alloy at 300°C with a hydrogen concentration of 30 ppm is in the range of J_{IC} = 38 ÷ 40 kJ /m^2. This is in good agreement with the experimental one, including the experimental errors.

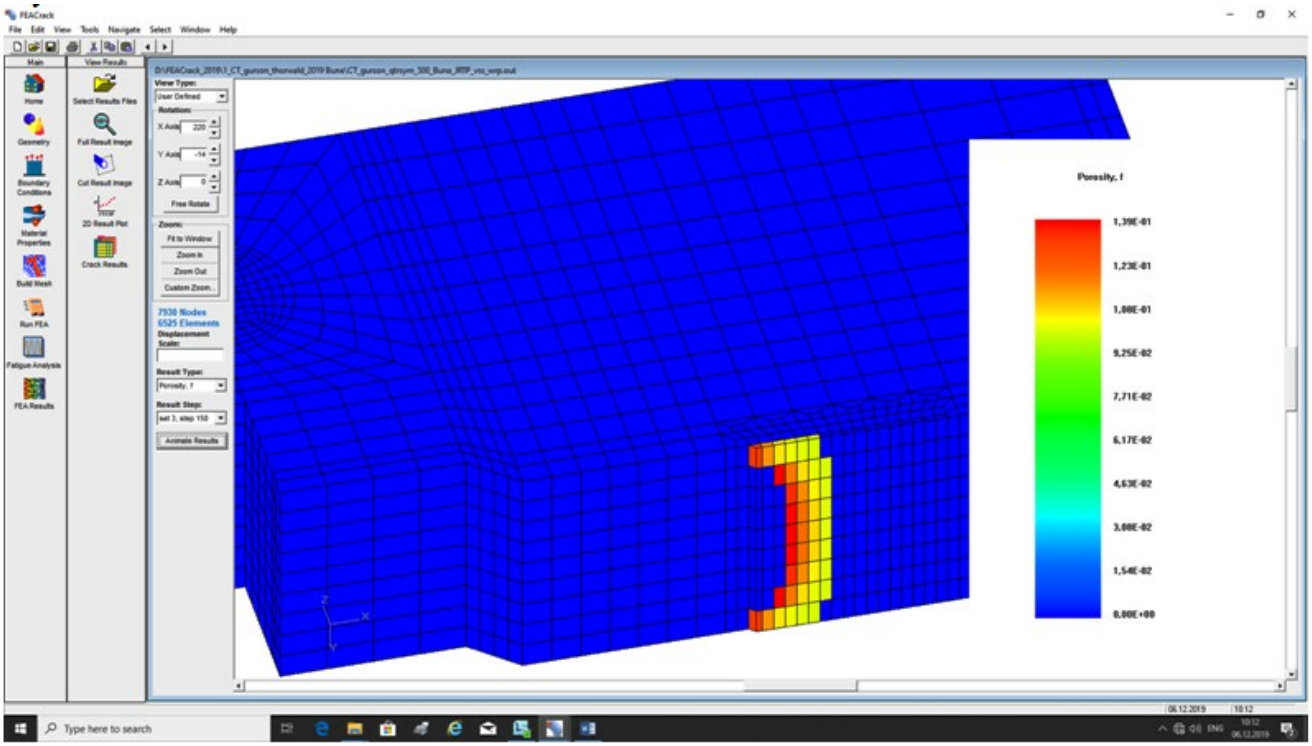


Fig. 2. The porosity of the elements in the crack front for CT specimen (FEACrack analyses, step 150)

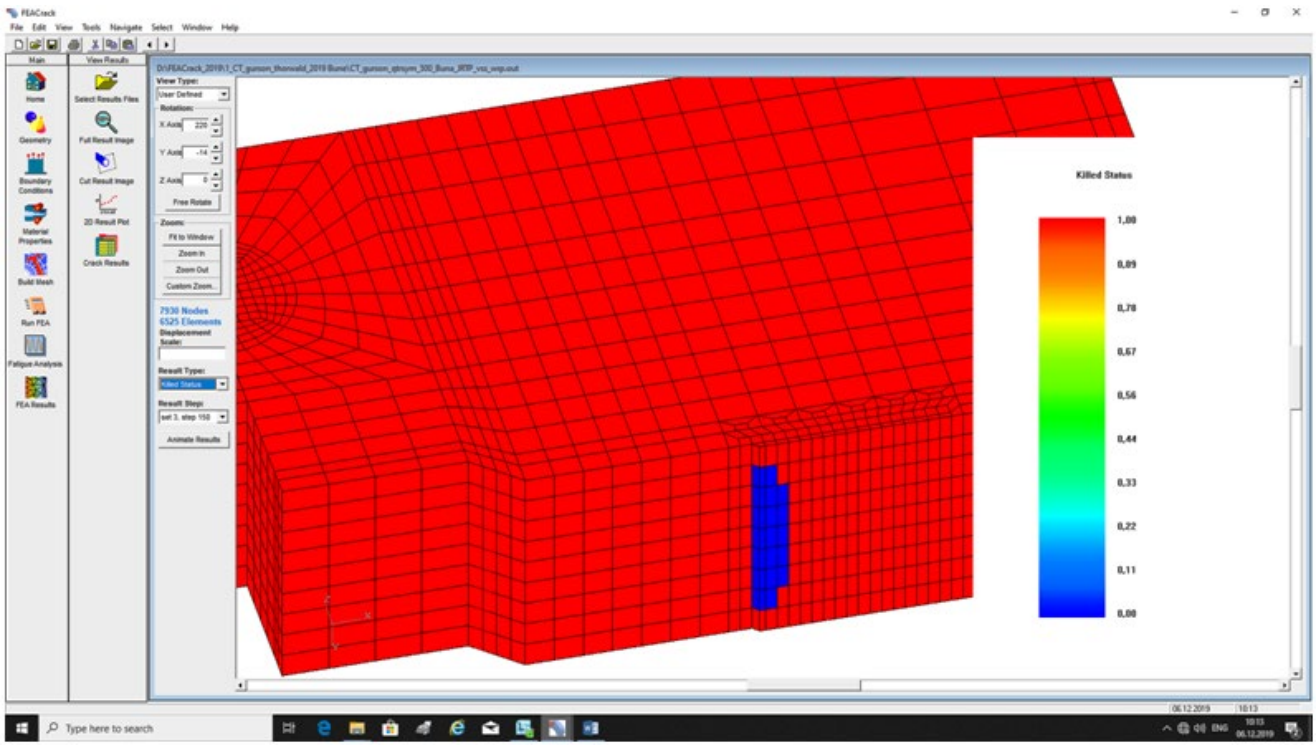


Fig. 3. The crack surface mark of CT specimen by killed elements (FEACrack analyses, step 150)

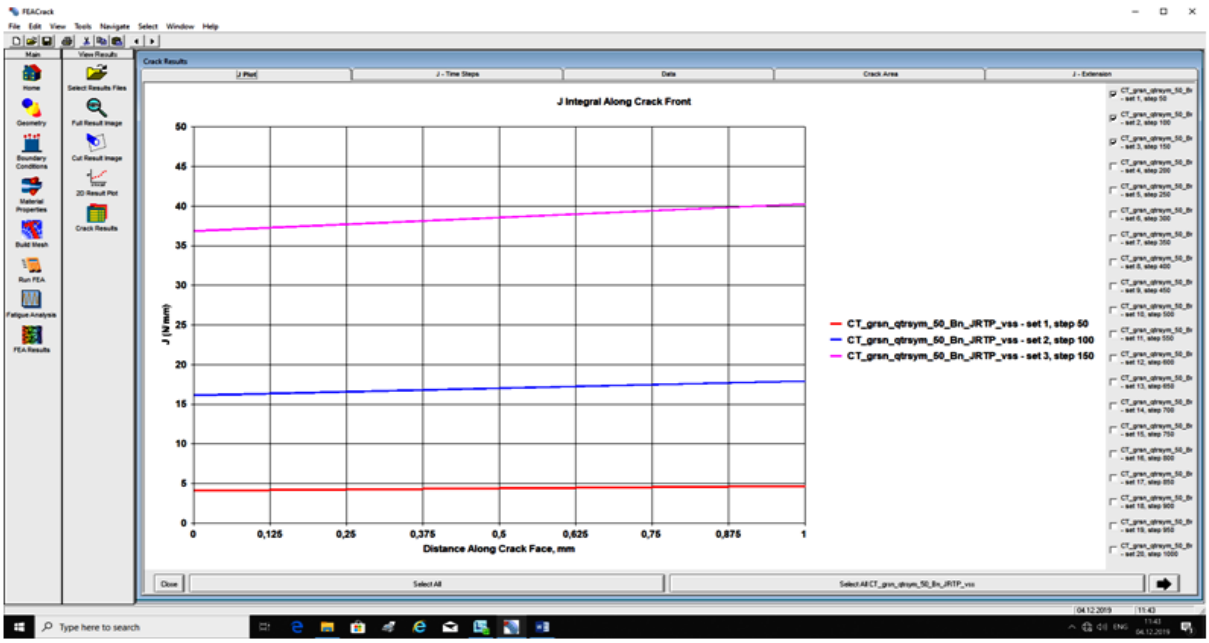


Fig. 4. J-integral values for CT specimen along the crack front at various steps

Conclusions

The paper describes a study on the crack initiation and growth modelling for the Zr-2.5%Nb CANDU pressure tube alloy, by using the Gurson-Tverggard-Needleman approach for the ductile fracture. The GTN model approach is based on the volume fraction of voids, which is included in the yield criterion.

To perform the finite element analyses (FEA) in the plastic domain of loading, the FEACrack software is used. To evaluate crack initiation and crack propagation under plasticity assumption, the ″porous material″ option was chosen. To perform crack initiation and propagation, the model considered the extinction of finite elements from the crack front. The fact was performed by de-cohesion when the achievement of the critical fraction of voids in the area is reached. The extinction of the finite elements on the front of the advancing crack happens when the material cohesion achieves the critical fraction of voids.

The experimental assessment of toughness of Zr-2.5% Nb expressed as J_{IC} was experimentally obtained in previous work, and the obtained value is J_{IC} = (35 ± 5) kJ /m^2. The *J*-integral values from FEACrack analyses, at a certain step of loading, are in the domain J_{IC} = 38 ÷ 40 kJ /m^2.

Also, by comparing the crack surface mark from FEACrack analyses with those from the experimental work, it was found that they are quite similar. Therefore, it can be concluded that fracture toughness of Zr-2.5%Nb alloy at 300°C is in the range J_{IC} = 38 ÷ 40 kJ /m^2.

The study is a part of the structural integrity assessment area developed in the framework of the Fuel Channel Programme, to support the evaluation of the in-service inspection results from Cernavoda NPP, Unit 1 and 2.

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