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On the Application of Rousselier's Damage Model to Predict Fracture Resistance Behavior of Zircaloy Fuel Pin Specimens

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Abstract

It may not be possible to machine standard fracture mechanics specimens from the thin-walled fuel pins as used in the nuclear reactors due to their geometry. In order to overcome this problem, a combined experimental and finite element (FE) analysis procedure has been adopted in this work. Determination of transverse mechanical properties from the ring type of specimens machined from the thin-walled nuclear reactor fuel pins is not also straightforward due to the presence of combined tension as well as bending loading conditions. However, finite element analysis of the whole ring tension setup can be carried out and the material stress-strain property can be determined through an inverse and iterative procedure. In this work, ring tension tests were carried out on un-irradiated Zircaloy-4 clad tube specimens. The specimen and the mandrel both were modeled in order to evaluate the load-displacement behavior of the test. The Rousselier's micro-mechanical model for ductile fracture was applied to simulate the crack growth in these specimens. The micro-mechanical parameters as determined from the ring tension experiment and finite element analysis were later used to simulate the crack propagation in a standard double-edged notched tensile (DENT) specimen. The J-R curve of the DENT specimen has also been compared with that of a cracked Pin-Loading-Tension (PLT) specimen.

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Keywords: Zircaloy-4 fuel pin; J-R curve; Rousselier's model

1. Introduction

Fuel pins as used in nuclear reactors are thin-walled tubes and are made up of Zirconium based alloys (i.e., for water-cooled reactors) due to their low neutron absorption cross-section [1]. In order to ensure a long resident time of these tubes in the reactor without leakage of radioactivity to the surrounding fluid, their fracture resistance behavior need to be evaluated. However, it is not possible to obtain standard fracture mechanics specimens from these tubes due to their geometry. In order to overcome this problem, a combined experimental and finite element (FE) analysis procedure has been adopted in this work.

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The FE analysis requires the mechanical property in terms of material stress-strain curve. Determination of transverse mechanical properties from the ring-type specimens machined from these fuel pins is also not straightforward [2]. It is because of the presence of combined tension as well as bending loading conditions due to the curvature of the specimens. On the other hand, FE analysis of the whole ring-tension test-setup can be carried out and the material stress-strain curve can be determined through an inverse and iterative procedure. For this purpose, ring-tension tests were carried out on un-irradiated Zircaloy-4 clad-tube specimens. Both the specimen and the loading mandrel were modeled to evaluate the load-displacement behavior of the test. By comparing the load-displacement response of FE analysis with that of experiment, the material stress-strain curve was evaluated. The above procedure was also verified by testing a ring-tension specimen (machined from carbon steel material) of similar dimension as that of the Zircaloy fuel-pin specimen and then comparing the stress-strain curve with that of a standard round tensile specimen. In order to simulate the load-drop in the ring-tension test due to the nucleation, growth and coalescence of micro-voids, Rousselier's damage model for ductile fracture was used in the FE analysis. The micro-mechanical parameters of Zircaloy-4 as determined from the ring tension experiment and finite element analysis were later used to simulate the crack propagation and fracture resistance (J-R) curve for a standard double-edged notched tensile (DENT) specimen. The J-R curve of the DENT specimen was also compared with that of an axially-cracked Pin-Loading-Tension (PLT) specimen.

2. Rousselier's model for simulation of ductile fracture

The micro-mechanical process of ductile fracture involves the processes of void nucleation, growth and coalescence. In order to consider the effect of this micro-mechanism in simulation of ductile crack growth, the continuum damage mechanics models need to be used in the finite element (FE) analysis. In this analysis, we use the Rousselier's model for simulation of crack growth in the ring tension as well as the DENT specimens of the Zircaloy-4 material. The yield function of the Rousselier's model is written as follows [3].

$$\phi = \frac{q}{1-f} + D\sigma_k f \exp\left(\frac{-p}{(1-f)\sigma_k}\right) - R\left(\varepsilon_{eq}\right) = 0 \tag{1}$$

where D and σ_k are the parameters of the Rousselier's model and are constants for a material. With loading, the void volume fraction evolves from the initial void volume fraction f_0 (volume fraction of eligible second phase particles responsible for nucleation of voids upon plastic deformation) in the material. At a critical void volume fraction f_c, the voids coalesce with each other and at the final void volume fraction f_f, the material points loses its stress carrying capability. Hence, the above three void parameters (i.e., f_0, f_c and f_f) are also the material properties of the damage model. The void growth rate is obtained using the plastic incompressibility condition of the matrix material as

$$\dot{f}_{growth} = (1-f)\,\dot{\varepsilon}_{kk}^{p} \tag{2}$$

where $\dot{\varepsilon}_{kk}^{p}$ is the change in hydrostatic component of the plastic strain tensor. For solving the boundary value problem of the damage continuum, one needs to solve the mechanical equilibrium equation

$$\nabla.\sigma + f_b = 0 \tag{3}$$

along with the associated boundary conditions, where σ is the Cauchy stress tensor and f_b is the body force per unit volume. The Rousselier's yield function is used for estimation of the onset of yielding of the material point in presence of porosity (e.g., void volume fraction) and the void volume fraction is considered as an internal state variable in the material constitutive model. For the FE analysis using Rousselier's model, the in-house code DEFINE has been used. The details of the FE implementation can be found in Ref. [4].

3. Results and discussion

In this work, specimens in the shape of rings of 3 mm width approximately were machined from the un-irradiated stress-relief annealed Zircaloly-4 fuel pins. These fuel pins are used in Indian Heavy Water Reactors. The inner diameter of the fuel pin specimen is 14.4 mm and the thickness is 0.4 mm. A typical ring tension specimen is shown in Fig. 1(a). The deformation (necking) of the specimen after loading is shown in Fig. 1(b). The loading fixture consists of two semi-cylindrical mandrels attached two a loading rod and it is shown in Fig. 1(c). The specimen and the loading mandrel have been modeled in FE simulation and the FE mesh is shown in Fig. 2. For the FE analysis, the material properties (such as yield stress, ultimate tensile strength and strain hardening exponents) have been initially guessed and the load-displacement curve has been compared with that of experiment. The true stress-strain curve of the material has been modified till a satisfactory agreement of the load-displacement data between experiment and FE analysis has been obtained. This is done in an iterative mode.

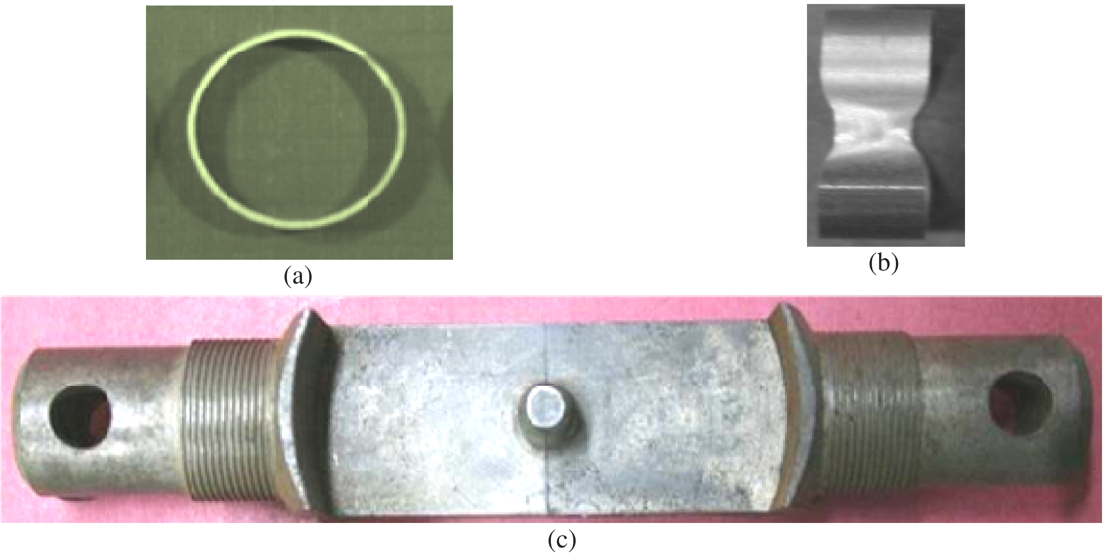

Fig. 1. (a) Picture of a ring tension specimen machined from the Zircaloy-4 fuel pin of Indian PHWR; (b) necking of the specimen after loading; (c) loading fixture used in the experiment.

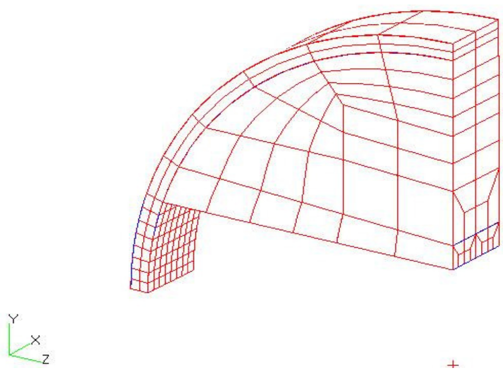

Fig. 2. Finite element mesh of the specimen and the loading mandrel.

The true stress-strain as obtained through this procedure has been compared with the data obtained from the conventional method. In the conventional method, the load-displacement data is converted to the engineering stress-strain data by using initial area and gauge length of the specimen. However, for this ring tension test, the gauge length is not known a priori and has been obtained from the shape of the necked region of the specimen as shown in Fig. 1(b). The engineering stress-strain data is then converted to the true stress-strain data using standard equations. The problem with this method is the determination of the gauge length and the condition of stress-state, which is not pure tension in this specimen (due to the curvature of the specimen). Hence, the inverse FE analysis procedure has inherent advantages for determining the mechanical properties from these non-conventional specimens.

The true stress-strain curve as obtained from FE analysis has been presented in Fig. 3 along with the stress-strain data as obtained from the conventional technique. It can be observed that the true stress-strain curve as obtained from inverse FE analysis shows a strain-hardening behavior whereas the data obtained from the conventional technique shows a flat curve after a strain of approximately 8%. This material is known to exhibit substantial strain hardening behavior at room temperature and hence, it can be observed that the data as obtained from FE analysis represents the material behavior satisfactorily. With this stress-strain data, the load-displacement behavior of another ring tension specimen was simulated and the data has been compared with that of experiment in Fig. 4. It can be noted the results of FE simulation are very close to that from experiment and hence, the material properties as obtained in this work are representative of the actual mechanical response at room temperature.

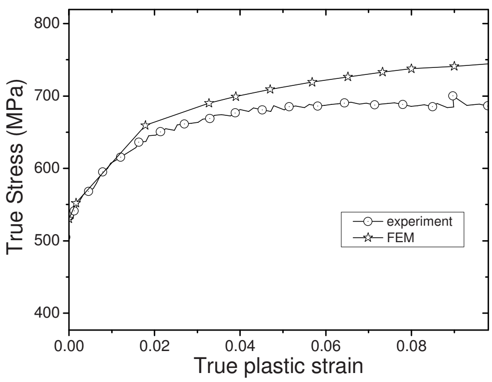

Fig. 3. True stress-strain curve of Ziracloy-4 as obtained from FEM and comparison with experimental data.

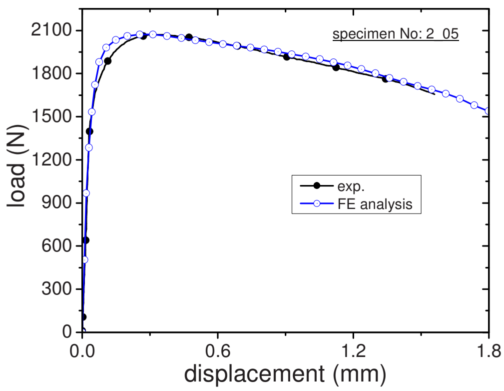

Fig. 4. Comparison of load-displacement response as obtained from FE analysis with that of experiment for a typical ring tension specimen.

In order to further verify the validity of the method, tests were carried for specimens machined from carbon steel. The advantage of this exercise is that one can machine standard round tensile specimens as well as ring tension specimens from the steel blocks. The round tensile specimens of 4 mm diameter and 20 mm gauge length were machined from this steel block. Similarly, ring tension specimens of 14.4 mm internal diameter, 0.4 mm thickness and 3 mm width were also machined and tested using the same experimental setup. The yield stress (YS) and ultimate tensile stress (UTS) data as obtained from the three methods (i.e., FE analysis, conventional tensile test and ring tension test) are presented with the help of bar chart in Fig. 5. Hence, it can be concluded that the inverse FE analysis as deployed in this work has been able to satisfactorily predict the material stress-strain data.

It may be noted that standard tensile specimens cannot be machined from fuel pin specimens obtained from nuclear reactors after different time periods of operation due to the geometry. Moreover, handling of irradiated specimen for the conventional tensile tests is a difficult task, whereas, simple ring specimens can be machined within hot-cells and the mechanical properties of the irradiated materials can be determined conveniently using the above mentioned combined FE analysis and experiment. In another task, the micro-mechanical parameters (initial void volume fraction, void volume fraction at coalescence, final void volume fraction) have been determined by simulating the load-drop in the ring tension specimens as shown in Fig. 6. The results of FE simulation with Rousselier's model has been compared with two experimental data of ring tension tests. The initial void volume fraction, void volume fraction at coalescence, final void volume fractions have been estimated as 0.001, 0.05 and 0.3 respectively. The Rousselier's constants (D and σ_k) have been taken as 2 and 600 MPa respectively.

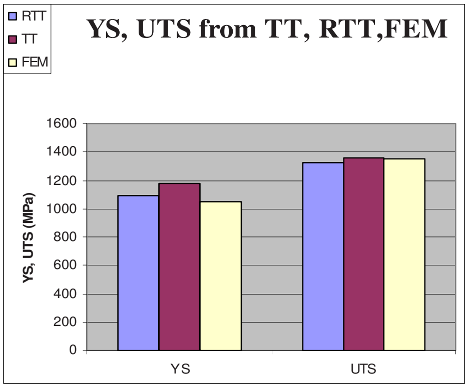

Fig. 5. Comparison of YS, UTS of the material as obtained from FE analysis, ring tension test and standard tensile test.

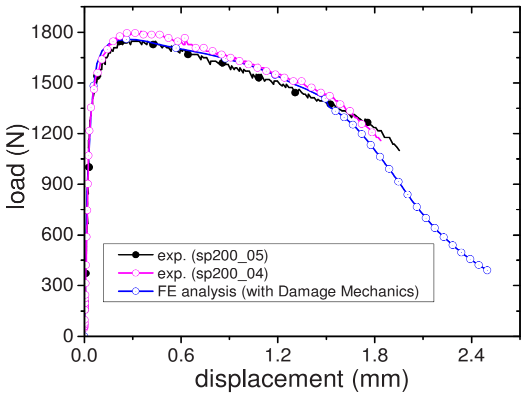

Fig. 6. Load-displacement curve as obtained from FE analysis of a ring tension and its comparison with experimental data.

The advantage of the continuum damage mechanics simulation is that the micro-mechanical parameters are transferable across different types of specimens and from specimens to components and hence, these can be used to simulate the fracture resistance behavior of Zircaloy-4 using standard facture mechanics specimens. For this purpose, a standard double-edged notched tensile (DENT) specimen with a width of 12.5 mm and initial crack length of 3.25 mm (on both sides) was simulated by FE analysis with the Rousselier's damage model. A 2D plane strain analysis (with unit thickness) was carried out. One-fourth of the specimen was simulated to take into account of symmetry in the geometry, boundary and loading conditions. A mesh size of 0.05 mm was used near the crack-tip. The J-R curve of the DENT specimen was obtained from the use of η factor in the area under the load-displacement curve and is presented in Fig. 7. In order to compare the J-R curve as obtained from the analysis of the standard DENT specimen, and the experimental J-R curve from the Pin-Loading-Tension (PLT) specimen are ~~is~~ presented in Fig. 7. The details of the PLT specimen and the experimental setup can be found in Ref. [5]. The PLT specimen is a non-standard specimen and it has been used in Ref. [5] to determine the J-R curve using load-normalization technique.

The advantage of the PLT specimens is that it can be directly machined from the fuel pin specimens and tested to determine the fracture resistance behavior which can be used for structural integrity analysis of the fuel pins in the nuclear reactor for different conditions of loading including those of postulated accident scenarios. The PLT specimens were machined from the same PHWR fuel pin lots as has been used to machine the ring tension specimens in this work. It was observed that the J-R curve of the DENT specimen is close to that of the PLT specimen though it is on the lower side, which is due to the use of 2D plane strain finite element analysis in simulation of the fracture behavior of the DENT specimen.

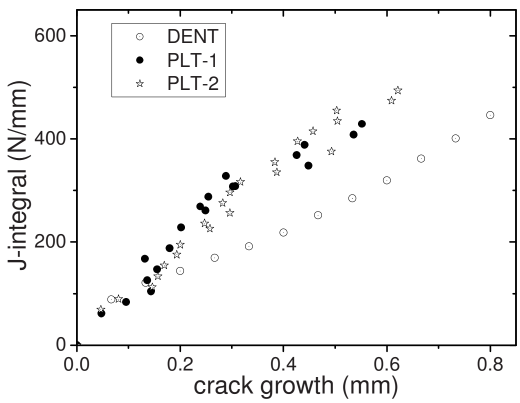

Fig. 7. J-R curve of the DENT specimen as obtained from FE analysis its comparison with that of the PLT specimen.

4. Conclusions

In this work, the ring tension tests were carried out on un-irradiated Zircaloy-4 clad tube specimens. Both the specimen and the mandrel were modeled through FE analysis to evaluate the load-displacement behavior of the test. By comparing the load-displacement response as obtained from finite element analysis with that of experiment, the material stress-strain curve was evaluated. In addition, Rousselier's micro-mechanical model for ductile fracture was applied in order to simulate the crack growth in these specimens. The micro-mechanical parameters as determined from the ring tension experiment and finite element analysis were later used to simulate the crack propagation in a standard double-edged notched tensile specimen. The J-R curve of the DENT specimen has also been compared with that of a cracked Pin-Loading-Tension specimen. It was observed that the parameters of the Rousselier's model are able to predict the fracture resistance behavior of cracked fuel pins specimens satisfactorily, which have been obtained through a combined experiment and FE analysis of the ring tensile specimens. Moreover, the mechanical properties were predicted unambiguously through the inverse FE analysis of the ring tension tests. Hence, this method can be used to determine the material properties of irradiated and service-aged fuel pins as obtained from the nuclear reactors after different periods of reactor operation. This will help in integrity analysis of the fuel pins for their extended residence time in the reactor.

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