MECHANICAL FATIGUE TESTS OF SEU-43 FUEL BUNDLE CLADDING AT 400°C

TESTE DE OBOSEALA MECANICA ASUPRA TECILOR FASCICULULUI SEU-43 LA TEMPERATURA DE 400°C

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Abstract: *This paper presents the testing method of samples worked from Zicaloy-4 tubes (“as-received’’ metallurgical state), utilized as cladding for the new CANDU SEU-43 fuel bundle. These tests are intended to simulate the cladding’s behavior in a power cycling process inside the reactor. The testing process is of low cycle fatigue type, done outside of the reactor, on “C-ring” samples, which are mechanically tested at 1%, 2% and 3% total amplitude deformation, at a temperature of 400°C. To determine the deformation for both types of tube (small and big diameter), a numerical simulation was done, using a finite element analysis in the ANSYS commercial computer code.*

Keywords: fatigue, CANDU SEU-43, Zircaloy-4, ANSYS

Rezumat: *Acest articol prezinta metoda de testare a probelor prelevate din tuburi de Zircaloy-4 (conditia metalurgica “in stare de livrare”), utilizate pentru intecuirea combustililului fasciculelor inovative CANDU SEU-43. Aceste teste sunt menite sa simuleze comportamentul tecilor intr-un proces de ciclaj de putere in interiorul reactorului. Testarea la oboseala este de tip oligociclic, in afara reactorului, efectuata pe probe de tip “C-ring”, care sunt incercate mecanic la amplitudinile totale ale deformarii de 1%, 2% si 3%, la o temperatura de 400°C. Pentru determinarea defromatiilor pentru ambele tipuri de tub (diametru mic si mare), s-a efectuat o simulare numerica, folosind analiza cu elemente finite in codul comercial ANSYS.*

Cuvinte cheie: oboseală, CANDU SEU-43, Zircaloy-4, ANSYS

1. Introduction

Most present day CANDU type reactors use a fuel bundle made up of 37 rods filled with natural uranium pellets. The functionality of the current fuel at extended burn degrees offers limited performance and because of this fact, a new fuel bundle concept, named SEU-43, was proposed. This new fuel bundle, with 43 fuel rods of

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two different diameters, uses low enriched uranium, obtained from the reprocessing of burnt fuel in LWRs. The SEU-43 fuel bundle represents an evolution of the standard CANDU fuel bundle with 37 elements.

This paper presents the testing method of samples worked from Zicaloy-4 tubes ("as-received'' metallurgical state), utilized as cladding for the CANDU SEU-43 fuel bundle. These tests are intended to simulate their behavior in a power cycling process inside the reactor. The testing process is of low cycle fatigue type, done outside of the reactor, on "C-ring" samples, cut along the transversal direction. These samples are mechanically tested at 1%, 2% and 3% total amplitude deformation, at a temperature of 400°C. To determine the deformation for both types of tube (small and big diameter), a numerical simulation using a finite element analysis in the ANSYS commercial computer code [1] was executed, which resulted in a set of calibration curves. The curves are dependent on the metallurgical state, as well as on the mechanical and microstructural characteristics of the material. For determining mechanical properties necessary for the simulation, tensile tests were done on Zircaloy-4 samples ("ring tensile test" samples) at a temperature of 400°C.

The fatigue test results are in the form of a fatigue life curve (N-ε) for each of the SEU-43 fuel bundle rod diameters. The curve is determined by the experimental dependency between the number of cycles to fracture (N) and the total deformation amplitude (Δε). The low cycle mechanical fatigue tests, done at 400°C outside of the reactor, together with electronic microscopy analysis have yielded results which reflect the characteristic behavior of the new fuel bundle Zircaloy-4 cladding in the given environmental conditions.

2. Establishing the Calibration Curves

The calibration curves are dependent on the metallurgical state, as well as on the mechanical and microstructural characteristics of the material. These curves represent the dependency between the deformation of the sample and the displacement of the piston, variables which can be measured with a strain gage and a displacement transducer. Every deformation (1%, 2% and 3%) is equivalent to a certain displacement of the piston which is measured by the transducer.

Having in mind that the measuring of the deformation poses the most difficulties because of the small dimensions of the sample, the elaborate techniques utilized for attaching the strain gages and the lack of high temperature resistant strain gages, an alternative was chosen to obtain the calibration curves: a finite element analyses in the ANSYS computer code [1].

Using this method, the calibration curves for the 1% ÷ 3% deformation domain were traced for "C-ring" samples, at a temperature of 400°C. For this, a transversal cross-section of the specimen was modelled (Figure 1).

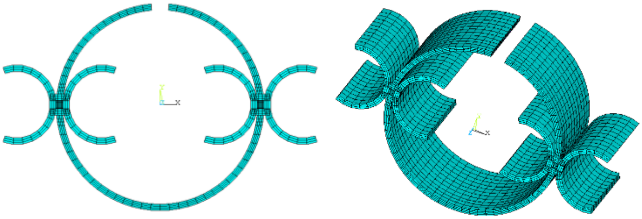

Figure 1. Modelling of "C-ring" samples using ANSYS

The code utilizes the material parameters (flow resistance, break resistance and elastic deformation) determined with the following formulas:

$$\varepsilon_{real} = \ln(1 + \varepsilon_{\exp}) \quad (1)$$

$$\sigma_{real} = \sigma_{\exp} \cdot (1 + \varepsilon_{\exp}) \quad (2)$$

where: (1) ε_{real} is the calculated deformation, σ_{real} is the calculated flow resistance; (2) ε_{exp} is the experimental deformation; σ_{exp} is the experimental flow resistance;

For determining mechanical properties, "ring tensile test" samples (Figure 2) were used.

Figure 2. „Ring tensile test" samples

3. The Fatigue Tests

The fatigue tests which simulate power cycling conditions inside the reactor were executed in conformity with references [2], [3], [4] and [5]. A series of five samples per deformation (1%, 2%, 3%), per diameter (small and big) were tested.

The ring shaped samples (Figure 3) were cut from SEU-43 Zircaloy-4 tubes.

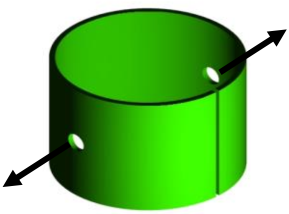

Figure 3. C-ring sample

4. Results

4.1. Calibration Curves

Firstly, the mechanical proprieties of the material were determined from the curves (Figure 4 and Figure 5) obtained from tensile tests at a temperature of 400°C. The graphs show a series of 5 „ring tensile test" samples per diameter.

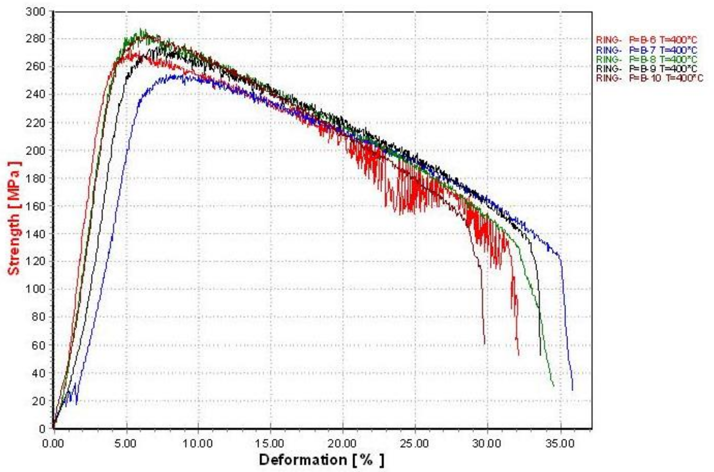

Figure 4. The experimental tensile curves for SEU-43 samples, big diameter (D), at 400°C

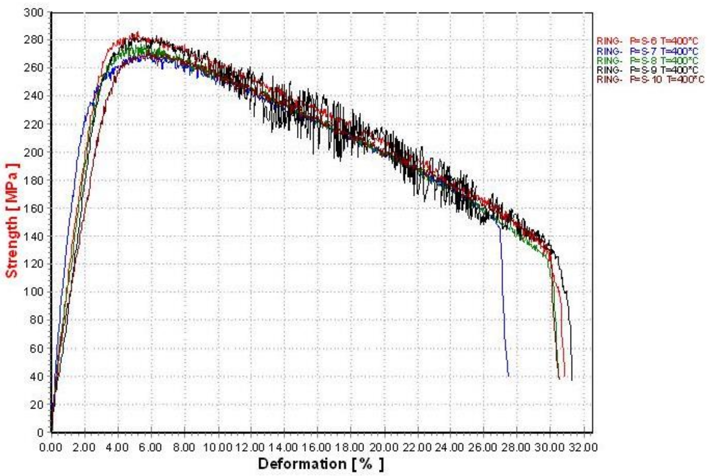

Figure 5. The experimental tensile curves for SEU-43 samples, small diameter (d), at 400°C

The mechanical parameters resulted from the calculated “real” curves are used for the ANSYS modelling. After the simulation, the results were compared with the results of calibrations done using strain gages and were found to be similar.

The calibration curve is the graphical representation of the dependency between the deformation of the sample and the displacement of the piston. The calibration curves obtained using the ANSYS code are represented in Figure 6 (SEU type I – big diameter) and Figure 7 (SEU type II – small diameter). The different curves are for calculations done in the central node and for mediation of multiple nodes starting from the central one. This mediation represents the length of the contact surface of the strain gage with the sample.

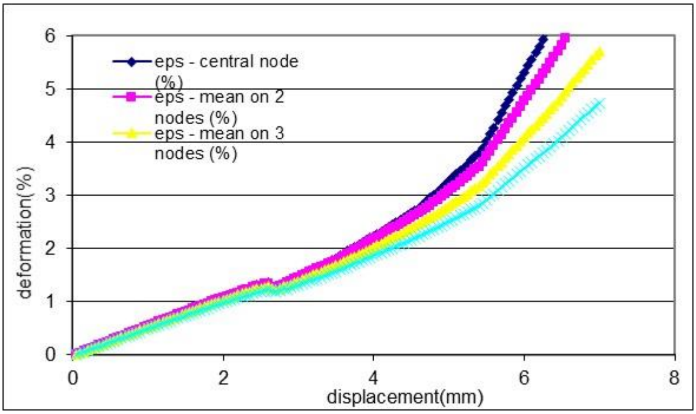

Figure 6. Piston displacement - deformation dependency at 400°C, when the fixing holes are drilled on the diameter axis of the big diameter (D) SEU-43 sample

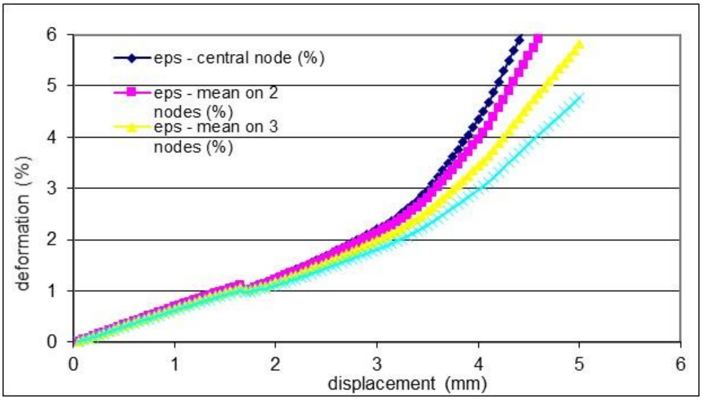

Figure 7. Piston displacement - deformation dependency at 400°C, when the fixing holes are drilled on the diameter axis of the small diameter (d) SEU-43 sample

It was established for both diameters that the best representation of the dependency between the deformation (1%, 2%, 3%) and the piston displacement is correlated by the curve for the central node, corresponding to the smallest possible area of contact with a strain gage.

4.2. Determination of the Durability Curve

The experimental data are presented in Figure 8 and Figure 9 in the form of a power curve dependent on the equation $N = f\left(\frac{\Delta\varepsilon}{2}\right)$ (3). A comparison was made with data from reference [5].

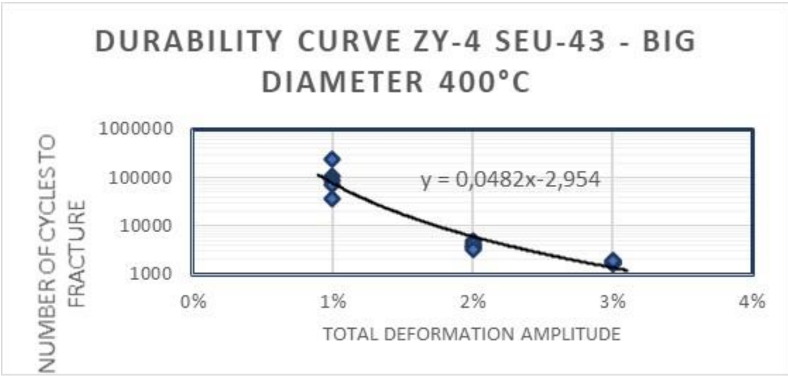

Figure 8. Durability Curve for Zircaloy-4, SEU-43, big diameter (D) samples, at 400°C

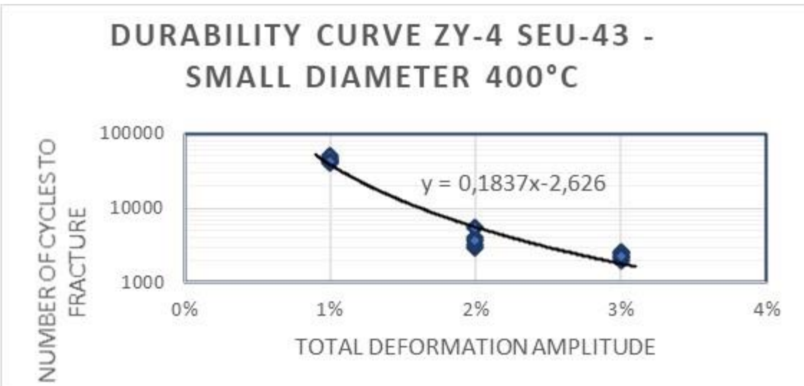

Figure 9. Durability Curve for Zircaloy-4, SEU-43, small diameter (d) samples, at 400°C

The curve functions respect the Coffin – Manson law: $\frac{\Delta\varepsilon}{2} \cdot N^{\alpha} = C$ (4)

4.3. Microstructural analysis of break surface

A SEM analysis was done on the fatigue test samples. The different aspects of the break surface are shown in Figure 10. The SEM analysis revealed the ductile-brittle break mode, done in phases along the fatigue striations, phenomenon present in all Zircaloy-4 fatigue tests.

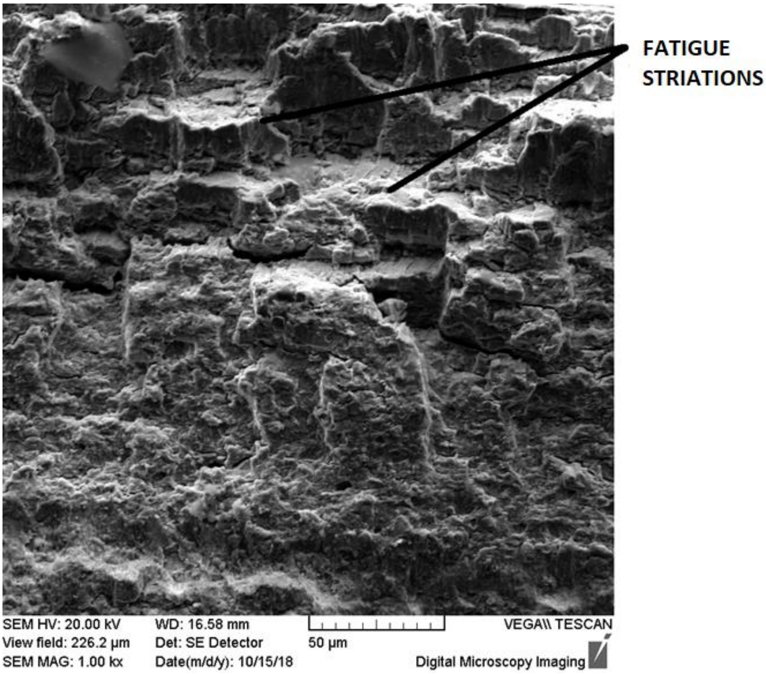

Figure 10. Zircaloy-4 break surface of fatigue sample at 400°C (x1000)

5. Conclusions

The fatigue tests described in this paper simulate power cycling conditions inside the reactor. The "C-ring" samples worked from Zircaloy-4 tubes ("as received" state) were tested outside of the reactor, at a temperature of 400°C for 1%, 2% and 3% amplitude deformation in accordance with ref. [3].

For determining the calibration curves, the finite element analyses in the ANSYS computer code was used. The prediction capacity of the ANSYS simulation was verified in a previous project, comparing the results of the calibration with the results from using strain gages, which were found to be acceptably close.

The results include the durability curve describing the behavior of "C-ring" samples worked from Zircaloy-4 tubes (as received state) subjected to low cycle fatigue tests done at 1%, 2% and 3% deformation amplitude.

The SEM analysis revealed the ductile-brittle break mode, done in phases along the fatigue striations, of the cycled fatigue tested samples.

R E F E R E N C E S

[1] ANSYS 7.1 Documentation.
[2] *M. Roth, C. Gheorghiu, V. Radu, V. Pitigoi, C. Ducu, V. Malinovschi, M. Abrudeanu* "Zircaloy-4 CANDU Reactor Sheaths Fatigue Lifetime", Progress of Cryogenics and Isotopes Separation Conference, Rm. Valcea, 2004.
[3] Standard Practice of Linearized Stress – Life and Strain – Life Fatigue Data, ASTM E 739 – 91.
[4] Testing Specification, "Fatigue tests done outside the reactor, which simulate power variations of CANDU fuel", INR-372000-400-002, Rev.0.
[5] *Toma Pana, Stefan Dan Pastrama* – Integrity of Metallic Structures, Ed. Fair Partners, Bucuresti, 2000.