FATIGUE TESTS ON SEU-43 ZIRCALOY-4 TUBES AT 350°C

TESTE DE CICLAJ PE TUBURI TIP SEU-43 DIN ZIRCALOY-4 LA 350°C

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Abstract: *Presently, the 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 doesn't offer the desired performance. Because of this fact, a new fuel bundle concept, named SEU-43, was proposed. This new concept 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.*

The paper presents the testing of samples worked from Zicaloy-4 tubes ("as-received'' metallurgical state), utilized in the composition of the CANDU SEU-43 fuel bundle. These tests are intended to simulate their behaviour 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 tested at 1%, 2% and 3% amplitude deformation, at a temperature of 350°C. To determine the amplitude deformation for both types of tube (small and big diameter), a numerical simulation must be done, using the finite element analysis in the ANSYS commercial computer code, resulting 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, tensile tests were done on Zircaloy-4 samples ("ring tensile test" samples) at a temperature of 350°C.

The fatigue test results are in the form of a fatigue life curve (N-ε) for Zircaloy-4 used in the SEU-43 fuel bundle. The curve is determined by the experimental dependency between the number of cycles to fracture and the deformation amplitude. The low cycle fatigue mechanical tests, done at 350°C, together with electronic microscopy analyses and microscopic grain analyses have reflected the characteristic behaviour of the zircaloy-4 metal in the given environmental conditions.

Keywords: low cycle fatigue, SEU-43, 350°C, ANSYS computer code

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Rezumat: *În prezent, reactoarele de tip CANDU utilizează un fascicul de combustibil alcătuit din 37 de teci umplute cu pastile de uraniu natural. Funcționalitatea combustibilului actual la gradele de ardere extinse nu oferă performanța dorită. Din acest motiv, a fost propus un nou concept de fascicul de combustibil, numit SEU-43. Acest nou concept utilizează uraniu cu un grad scăzut de îmbogățire, obținut prin reprocesarea combustibilului ars în LWR-uri. Fasciculul de combustibil SEU-43 reprezintă o evoluție a fasciculului standard de combustibil CANDU cu 37 de elemente.*

Lucrarea prezintă testarea probelor prelucrate din tuburile de Zicaloy-4 (stare metalurgica "as-received"), utilizate în compoziția fasciculului de combustibil CANDU SEU-43. Aceste teste sunt destinate să simuleze comportamentul lor într-un proces de ciclaj a energiei în interiorul reactorului. Procesul de testare este de tip oligociclic, efectuat în afara reactorului, pe eșantioane "C-ring", prelevate pe direcția transversală. Aceste probe sunt testate la o amplitudine a deformarii totale de 1%, 2% și 3%, la o temperatură de 350°C. Pentru a determina amplitudinea deformarii pentru ambele tipuri de tuburi (diametru mic și mare), trebuie făcută o simulare numerică, folosind codul numeric comercial cu elemente finite ANSYS, rezultând un set de curbe de calibrare. Curbele sunt dependente de starea metalurgică, precum și de caracteristicile mecanice și microstructurale ale materialului. Pentru determinarea proprietăților mecanice, testele de tracțiune au fost efectuate pe eșantioane din Zircaloy-4 (probe de tip "ring-test") la o temperatură de 350°C.

Rezultatele testelor de oboseală sunt sub forma unei curbe de durabilitate (N-ε) pentru teci de Zircaloy-4 utilizate în fasciculul de combustibil SEU-43. Curba este determinată de dependența experimentală dintre numărul de cicluri până la fisură și amplitudinea totala a deformării. Testele mecanice de oboseală oligociclice, efectuate la 350°C, împreună cu analizele microscopice electronice și analizele microscopice de graunte au reflectat comportamentul caracteristic al aliajului Zircaloy-4 în condițiile de mediu date.

Cuvinte cheie: oboseala oligociclică, SEU-43, 350°C, codul numeric ANSYS

1. Introduction

Presently, the 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 doesn't offer the desired performance. Because of this fact, a new fuel bundle concept, named SEU-43, was proposed. This new concept uses low enriched uranium, obtained from the reprocessing of burnt fuel in LWR type reactors. The SEU-43 fuel bundle represents an evolution of the standard CANDU fuel bundle with 37 elements.

Based on a technology developed at ICN Pitesti and on material specifications and fabrication tolerance imposed through the SEU-43 fuel bundle project, attempts were made to formulate a series of demands which will constitute the base for a quality control plan focused on ICN's own experimental research.
In this paper, a mechanical testing of Zircaloy-4 is presented. This material is used in the forging of two different diameters (small and big) tubes used to encapsulate the SEU-43 fuel.

The fatigue tests done outside the reactor for non-irradiated Zircaloy-4 tubes were thought up and realised at ICN. These fatigue tests will help in estimating the durability curves and other parameters that influence fatigue behaviour.

The testing processes of low cycle fatigue type, done outside the reactor, on “C-ring” samples, cut along the transversal direction. These samples are tested at 1%, 2% and 3% amplitude deformation, at a temperature of 350°C.

The testing equipment for “C-ring” samples was built at ICN and is capable of performing fatigue tests, being able to control displacement in the horizontal plane with the help of the proper transducer. For every sample deformation (1%, 2%, 3%), there is a corresponding displacement of the piston, measured by the transducer in millimetres.

The durability curve represents the fatigue behaviour of the cladding material. In this case it is obtained for a temperature of 350°C. In the current paper, having in mind the absence of high temperature resistant strain gages, the deformation calibration of “C-ring” samples, was done using finite element analysis in the ANSYS computer code [1].

Using the experimental data resulted from the tests, the durability curves are graphically traced for each type of sample (big and small diameter) and for metallurgical and microstructural state mentioned in the testing matrix.

2. Experimental set-up

2.1. Installation presentation

The fatigue testing equipment (Figure 1) was designed and built in 2002 at ICN and is used to test multiple types of samples.

Figure 1. The equipment used for simulated power cycling fatigue

The sample holders (Figure 2) are two “yoke”-like pieces, one of which is fixed to the support beam of the testing chamber, the other being coupled with a crank gear system, necessary for cyclic movement.

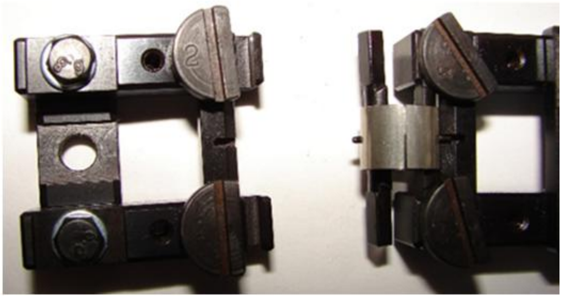

Figure 2. Sample holders

The command and data acquisition operations are handled by the Split Monitor Software. This application is developed and adapted for the Windows XP Operating System.

2.2. Sampling Process

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

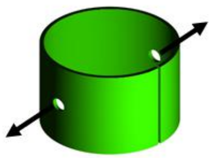

Figure 3. C-ring sample

3. Fatigue Test

3.1. 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 central 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 in millimetres.

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: the 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 350°C. For this, a transversal cross-section of the specimen was modelled (Figure 4).

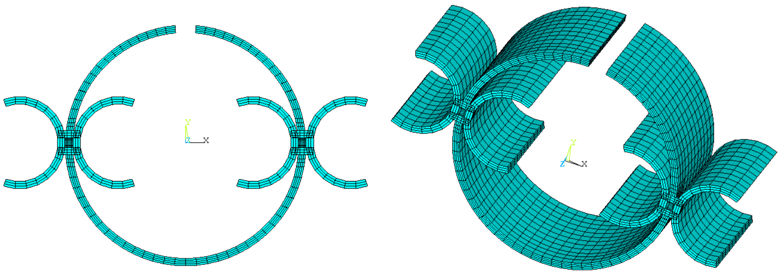

Figure 4. Modelling of "C-ring" samples using ANSYS

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

$$\varepsilon_{real} = \ln(1+\varepsilon_{\exp}) \qquad \sigma_{real} = \sigma_{\exp}\cdot(1+\varepsilon_{\exp})$$

Where: ε_{real} is the calculated deformation; σ_{real} is the calculated flow resistance;
For determining mechanical properties, "ring tensile test" samples (Figure 5) were used.

Figure 5. „Ring tensile test" samples

The experimental values were determined from the curves (Figure 6 and Figure 7) obtained from tensile tests at a temperature of 350°C.

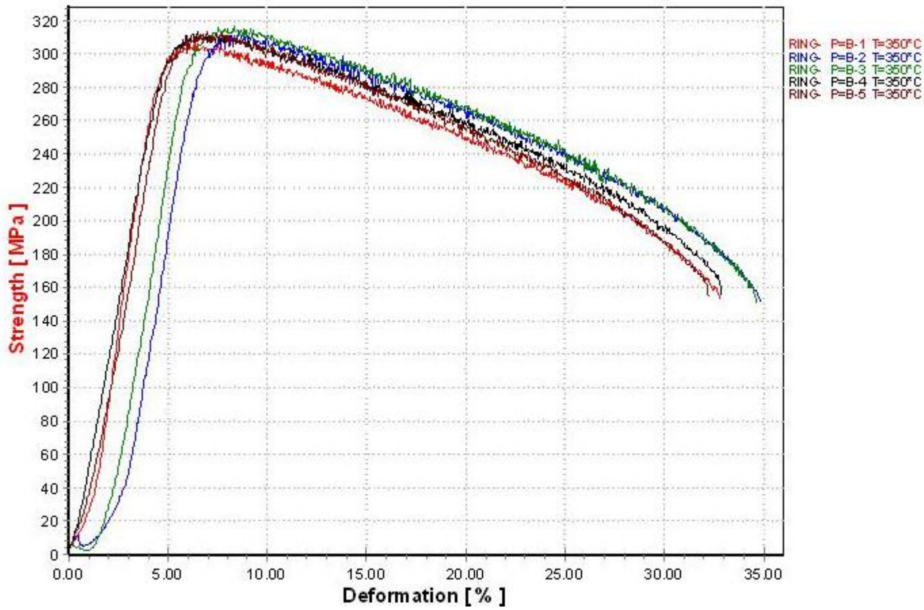

Figure 6. The experimental tensile curves for SEU-43 samples, big diameter (D), at 350°C

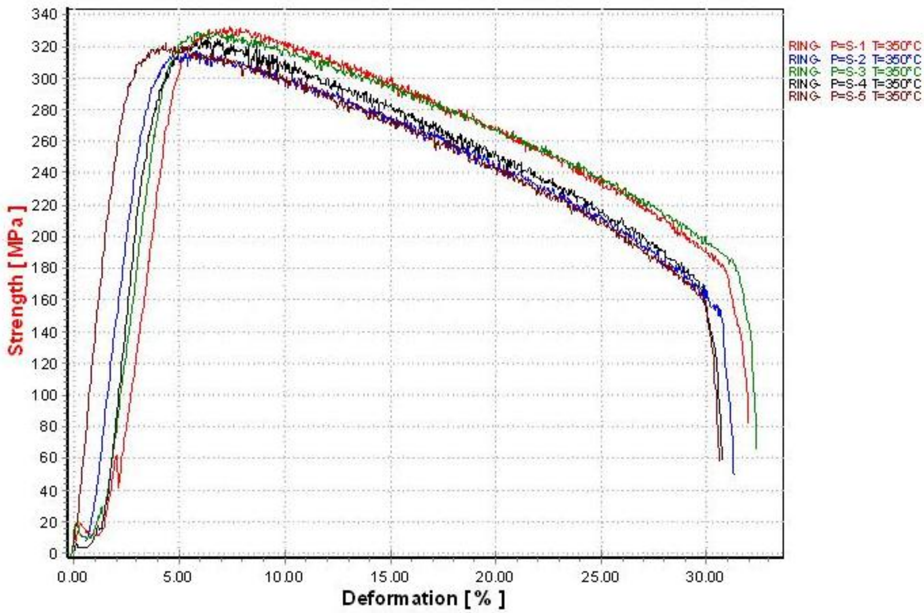

Figure 7. The experimental tensile curves for SEU-43 samples, small diameter (d), at 350°C

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.

3.2. The Fatigue Tests

The fatigue tests which simulate power cycling conditions inside the reactor were executed in conformity with references [2], [3], [4], [5] and [6]. A series of five samples per deformation (1%, 2%, 3%), per diameter (small and big) were tested.

4. Results

4.1. Calibration Curves

The calibration curve is the graphical representation of the dependency between the central deformation of the sample and the displacement of the piston. The calibration curves obtained using the ANSYS code are represented in Figure 8 (SEU type I – big diameter) and Figure 9 (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.

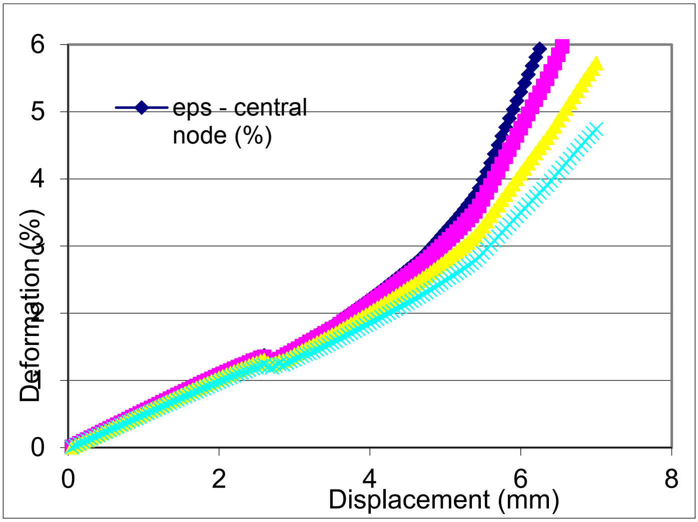

Figure 8. Piston displacement - deformation dependency at 350°C, when the fixing holes are drilled on the diameter axis of the big diameter (D) SEU-43 sample.

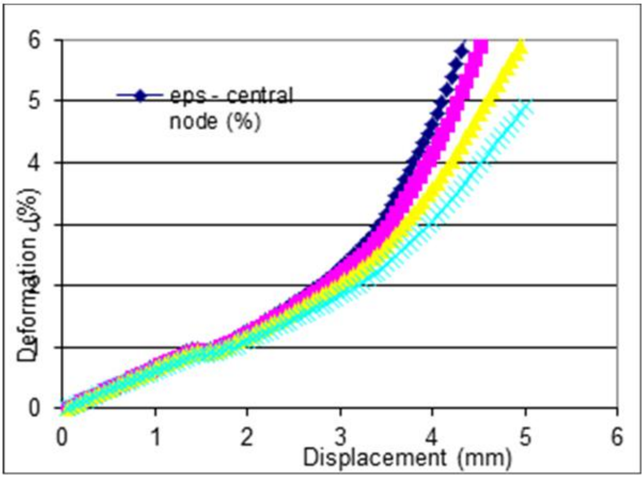

Figure 9. Piston displacement - deformation dependency at 350°C, when the fixing holes are drilled on the diameter axis of the small diameter (d) SEU-43 sample.

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, coresponding to the smallest possible area of contact with a strain gage.

4.2. Determinating the Durability Curve

The experimental data are presented in Figure 10 and Figure 11 in the form of a power curve dependent on the equation . A comparison was made with data from references [6] and [7].

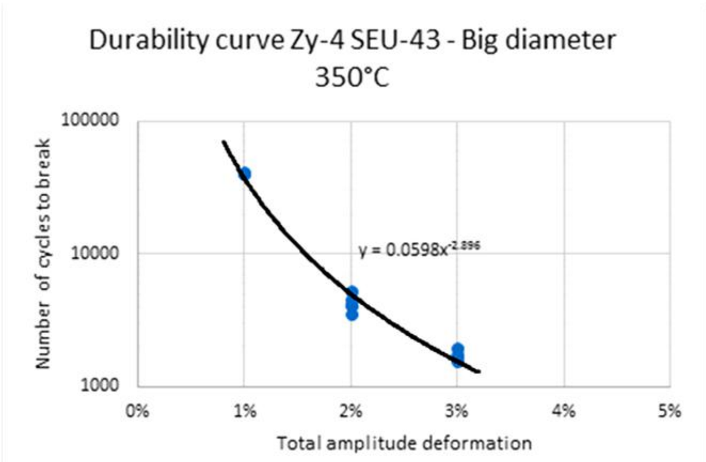

Figure 10. Durability Curve for Zircaloy-4, SEU-43, big diameter(D) samples, at 350°C

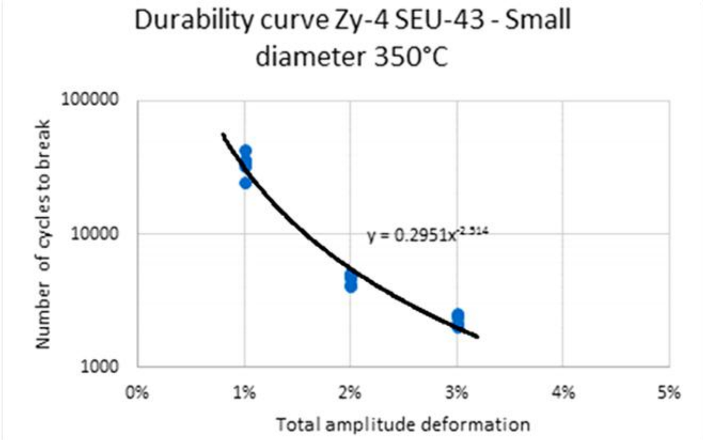

Figure 11. Durability Curve for Zircaloy-4, SEU-43, small diameter(d) samples, at 350°C

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

4.3. Microstructural analysis of break surface

A SEM analysis was done on the fatigue test samples. The different aspencts of the break surface are shown in Figure 12. The SEM analysis revealed the ductile-brittle break mode, done in phases along the fatigue striations, phenomenon present in all Zircaloy-4 fatigue tests.

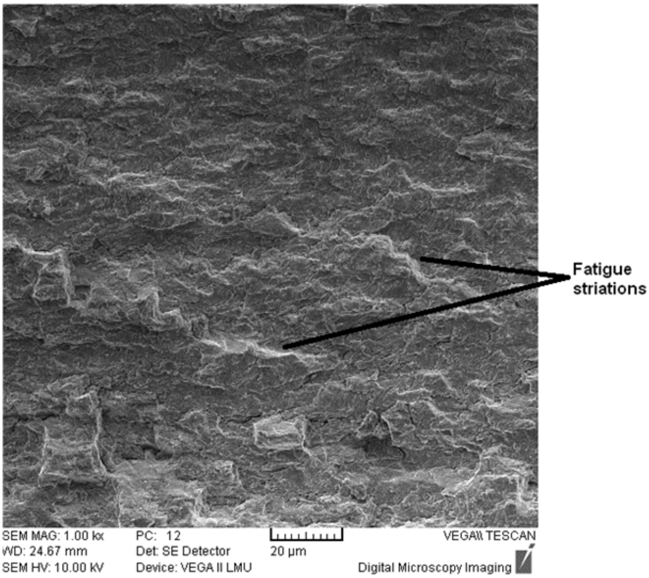

Figure 12. Zircaloy-4 break surface of fatigue sample at 350°C (x1000)

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 using an installation designed and built at ICN. The tests were done at a temperature of 350°C for 1%, 2% and 3% amplitude deformation in accordance with ref. [4].

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 behaviour 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 of the cycling 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] M. Tayal, A. M. Manzer, R. Sejnoha – The integrity of CANDU Fuel During Load Following, AECL, 1991.
[4] Standard Practice of Linearized Stress – Life and Strain – Life Fatigue Data, ASTM E 739 – 91.
[5] Testing Specification, "Fatigue tests done outside the reactor, which simulate power variations of CANDU fuel", INR-372000-400-002, Rev.0
[6] Toma Pana, Stefan Dan Pastrama – Integrity of Metallic Structures, Ed. Fair Partners, Bucuresti, 2000.
[7] Palleck Steve, Waheed Asif, Sim Ki-Seob, AECL Document, 2009.