GENERALIZATION OF THE COFFIN-MANSON RELATIONSHIP TO ASSESS THE LOW CYCLE FATIGUE FOR THE ZIRCALOY-4 FUEL SHEATH

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Abstract

In nuclear reactors, situations of power variation occur, such as power jumps during refuelling, and scheduled shutdowns, these having as a consequence the cyclical stress on the fuel elements sheath. The paper presents the results of the mechanical fatigue tests performed using the installation designed and made in RATEN ICN Pitesti. The experimental tests were carried out on samples of tubes made of Zircaloy-4 alloy, used for sealing SEU43 (Slightly Enriched Uranium) type nuclear fuel at temperatures ranging from 25° C to 400 °C, at total deformations of 1%, 2% and 3%. Based on the experimental results of the mechanical fatigue tests, the "durability curves" were obtained by representing the number of cycles until the final fracture as a function of the deformation amplitudes. At the same time, the influence of other parameters affecting the fatigue behaviour of the Zircaloy-4 alloy was monitored. The Scanning Electron Microscopy analysis revealed the nature of the fracture surfaces, specific to mechanical fatigue fracture. The experimental data obtained during several series of tests were used to develop a generalized Coffin-Manson relationship, which characterizes the "low cycle fatigue" (LCF) fatigue phenomenon of tubes made of Zircaloy-4 alloy. The parameters α and C, from the Coffin – Manson relation, contain in the form of analytical dependencies the test conditions, the temperature and the amplitude of the plastic deformation, for the range of plastic deformations between 1% and 3%, and for the temperature range T= 25 ° C – 400 ° C.

Keywords: *Low cycle fatigue, Coffin - Manson law, Zircaloy-4 alloy, Fuel element sheath*

Introduction

Currently, to fabricate the fuel elements sheath, essential components of nuclear power reactors, the zirconium alloy, Zircaloy-4, is used, considering its high resistance to mechanical stress, to corrosion and the low values of the effective neutron absorption section.

The sheath of the fuel element represents one of the protective barriers against the release of fission products in the coolant, having, at the same time, the ability to minimize corrosion, and the absorption of hydrogen and deuterium. The Zircaloy-4 sheath also accommodates the effects of deformation resulting from the pellet-sheath interaction and ensures the necessary structural properties so that it can withstand the thermomechanical loads imposed by the loading-unloading operations.

Considering the power variation situations that occur in the reactor, such as power jumps during refuelling, and scheduled shutdowns, respectively, the fuel element sheath is subjected to cyclical mechanical stresses, such as mechanical fatigue, sometimes in the field of small plastic deformations. Thus, it is necessary to study the behaviour of the fuel elements sheath under mechanical fatigue in the field of elastoplastic stresses, called in the specialized literature "Low Cycle Fatigue" (LCF).

This way, the particularities of the fatigue behaviour of Zircaloy-4 tubes can be highlighted when they are subjected to these power variations, in the temperature conditions specific to the operation of CANDU-type reactors.

Regarding the use of a certain type of fuel, the worldwide trend is to use a fuel with an extended burnup degree that would lead to an increase in the efficiency of fuel cycles and a reduction in the amount of spent fuel. From here it comes directly economic implications regarding reduced expenses with raw materials and spent fuel intermediate and final storage.

The paper presents several results of the mechanical cycling tests performed on Zircaloy-4 samples used in the sealing of SEU43 type nuclear fuel, at temperatures in the range of 25 ° C - 400 ° C and at total deformations of 1%, 2% and 3%.

The goal was to highlight their LCF type fatigue behaviour. This allowed obtaining a generalization of the Coffin-Manson equation, which can be used as a failure criterion in the analyses carried out with the help of calculation codes.

The test facility and the calibration curves establishment

To establish the calibration curves, necessary in the LCF-type experimental tests, in a preliminary stage, Zircaloy-4 alloy mechanical properties were determined by using ANSYS software, based on the finite element method. To keep the mechanical stress configuration specific to the fatigue tests, the mechanical properties were determined at temperatures in the range of 25 ^{o} C - 400 ^{o} C, through tensile tests of the "Ring Tensile Test" (RTT) type. The samples specific to this type of test are cylindrical so that the mechanical stress is circumferential, they being taken from the Zircaloy-4 type SEU43 tubes.

The LCF type tests, which are fatigue tests in the elastoplastic field, were performed on "C"-ring AR (As Received) type samples taken as rings in the transverse direction from SEU (Slightly Enriched Uranium) type tubes of two diameters: with inner diameter type d=13.5 mm, marked "SEU 43-D" and with inner diameter d=11.5 mm, marked "SEU43-d".

The experimental installation for performing LCF-type fatigue tests of samples made of Zy-4 tubes was designed and realized in RATEN ICN Pitesti (see Fig. 1). The installation has been improved over several years, taking into account the experience of its use and the need to increase the accuracy of measurements [1, 2].

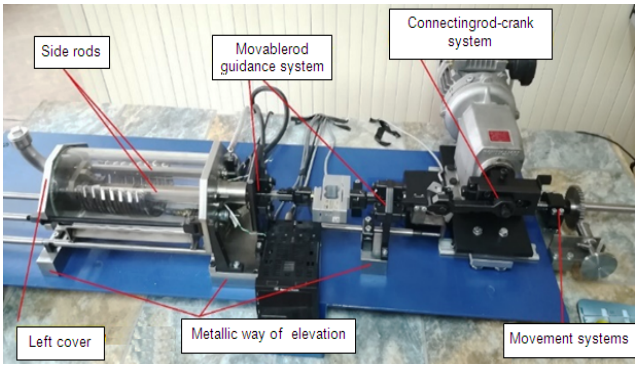


Fig. 1. The installation for performing the LCF type mechanical fatigue tests

Ordering and data acquisition operations were carried out by using the "Split Monitor" software application. This program intended for mechanical fatigue tests allows the recording of physical quantities in real-time (force, displacement, number of cycles) and the drawing of curves (force-displacement) based on the signals received from the sensors and the calibration tank. Setting the main test parameters for each tested sample and viewing the acquired data was done using the software interface [3, 4].

The samples were taken by turning from the Zircaloy-4 tube length in the form of rings with a width of 10 mm. To clamp the sample in the test device, two holes (with a diameter of 1.3 mm at 180° from each other) were drilled and by milling a slot was cut on the generator located in the middle of the distance between the two holes, according to the sketch given in Fig. 2.

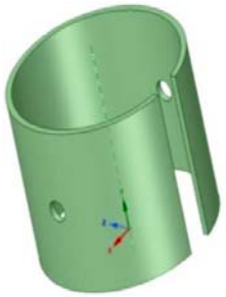


Fig. 2. The Zircaloy-4 sample of C-ring type

The calibration curves show the dependence between the value of the deformation concentrated in the centre of the sample and the displacement of the guide rod, quantities that can be measured with tensiometric stamps, and displacement transducer, respectively. Considering the lack of tensiometric stamps resistant to high temperatures for carrying out calibration tests on instrumented samples, it was decided to obtain the calibration curves by mathematical simulation using the ANSYS finite element calculation code. The calibration curves obtained are used to establish the displacement of the piston for various total deformations of 1%, 2% and 3%, respectively, necessary to perform the mechanical fatigue tests of the LCF type.

From the calibration curves, the correspondence between the deformation in the central node of the tested sample and the displacement of the piston was established for both types of samples (SEU43-D and SEU43-d) and the three deformations (1%, 2% and 3%) of the sample material at temperatures ranging from 25°C to 400°C.

Determination of the durability curves

Following the mechanical fatigue tests of the LCF type, the "durability curves" were obtained. These curves express the dependence "*Number of cycles to failure versus Amplitude of total deformation*". Durability curves were obtained for each type of sample provided in the test matrix, monitoring other parameters that influence the fatigue behaviour of the Zircaloy-4 alloy [5 - 8].

To express analytically the calibration curve, the dependence of the amplitude of the total deformation was represented in function of the number of cycles until breaking:

$$\frac{\Delta\varepsilon}{2} = f(N) \tag{1}$$

where: N - number of cycles to failure; $\frac{\Delta\varepsilon}{2}$ - amplitude of the total deformation.

The durability curves comply with the law:

$$\frac{\Delta\varepsilon}{2} = C \cdot N^{-\alpha} \tag{2}$$

Eq. (2) is known in the specialized literature as the Coffin-Manson relationship and it is used to represent the results obtained in the mechanical fatigue tests of the LCF type. Such a curve is represented in Fig. 3.

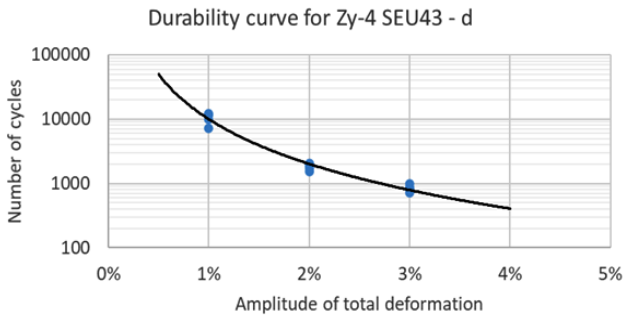


Fig. 3. The Coffin – Manson durability curve for the C-ring sample made of Zircaloy-4 sheath, SEU43-d

Microstructural analysis of fracture surfaces through mechanical fatigue

During the mechanical fatigue stress of the LCF type, the crack initiation occurs in the location with maximum plastic deformation, located in the centre of the sample on the inner surface of the ring, after which it propagates through its wall to the outside, until the final rupture (as presented in Fig. 4).

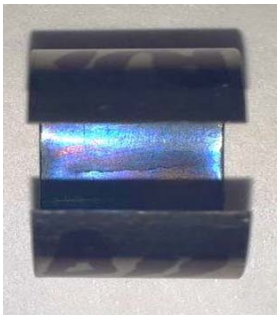


Fig. 4. Crack initiation in LCF tests on C-ring sample

The SEM (Scanning Electron Microscopy) examination of the fracture surfaces highlighted the ductile fracture mode and the appearance of striations characteristic of mechanical fatigue fractures in the crack propagation regions (see Fig. 5). These fatigue striations occurred due to cyclic stress, and their formation is the result of cyclic plastic deformation.

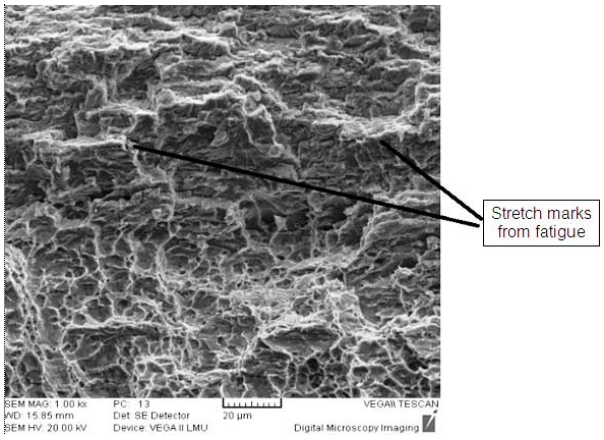


Fig. 5. SEM aspects of the fracture surface (x1000)

Generalization of the Coffin-Manson fatigue curve

An important objective is to generalize the Coffin-Manson-type fatigue curve [9] so that it contains the test variables temperature and plastic deformation amplitude. The results of the fatigue tests were processed in the MATLAB programming environment, so that in the Coffin - Manson relationship, the parameters α and C contain explicit functions of the test conditions, rendered by the temperature and the amplitude of the plastic deformation, considering the two types of diameters of the tested Zircaloy-4 sheaths.

To achieve this, the experimental database consisting of the values of the lifetime (expressed as the number of cycles to failure), the amplitude of the plastic deformation and the test temperatures were used to obtain some interpolation functions. The chosen functions have polynomial forms of degree II:

$$\alpha\left(T,\frac{\Delta\varepsilon}{2}\right)=A_1+B_1\cdot T+C_1\cdot\left(\frac{\Delta\varepsilon}{2}\right)+D_1\cdot T^2+E_1\cdot T\cdot\left(\frac{\Delta\varepsilon}{2}\right) \quad (3)$$

$$C\left(T,\frac{\Delta\varepsilon}{2}\right)=A_2+B_2\cdot T+C_2\cdot\left(\frac{\Delta\varepsilon}{2}\right)+D_2\cdot T^2+E_2\cdot T\cdot\left(\frac{\Delta\varepsilon}{2}\right) \quad (4)$$

Thus, the Coffin–Manson equation becomes:

$$\frac{\Delta\varepsilon}{2}=C\left(T,\frac{\Delta\varepsilon}{2}\right)\cdot N^{-\alpha\left(T,\frac{\Delta\varepsilon}{2}\right)} \quad (5)$$

The parameters given by Eqs. (3) and (4) for the two types of tested samples LCF, SEU-D and SEU-d, are as follows:

Zircaloy-4 sheath, type SEU 43-D

- for α_D : $A_1 = -0.008788$
  $B_1 = 0.01655$
  $C_1 = 2.57 \times 10^{-14}$
  $D_1 = -2.304 \times 10^{-5}$
  $E_1 = -1.623 \times 10^{-16}$
- for C_D : $A_2 = 0.4495$
  $B_2 = -0.002623$
  $C_2 = -3.383 \times 10^{-15}$
  $D_2 = 4.116 \times 10^{-6}$
  $E_2 = 6.763 \times 10^{-18}$

The 3D representation of the interpolation given by Eq. (3) for the α_D parameter is shown in Fig. 6; for the C_D parameter, the 3D interpolation according to Eq. (4) is presented in Fig. 7. The proposed equations provide a fairly good prediction of the experimental data.

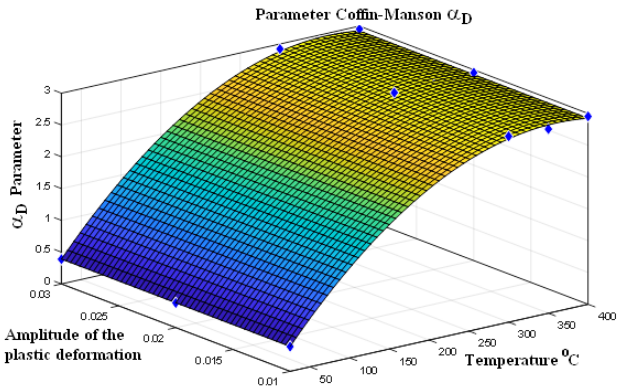


Fig. 6. 3D representation of $\alpha_D = f\left(T,\frac{\Delta\varepsilon}{2}\right)$

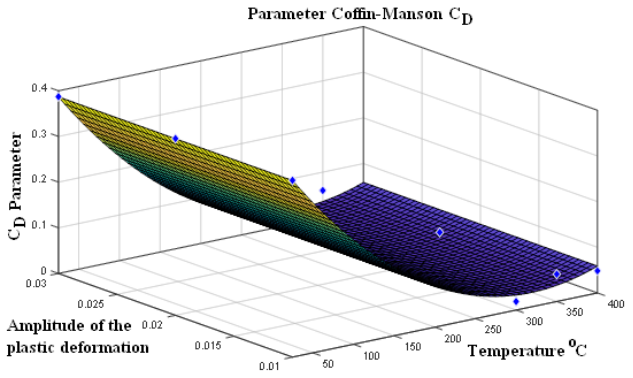


Fig. 7. 3D representation of $C_D = f\left(T, \frac{\Delta\varepsilon}{2}\right)$

Zircaloy-4 sheath, type SEU 43-d

- for α_d : $A_1 =$ 0.08144
  $B_1 =$ 0.01072
  $C_1 =$ 1.233 x 10^{-14}
  $D_1 =$ - 1.087 x 10^{-5}
  $E_1 =$ - 1.082 x 10^{-16}
- for C_d : $A_2 =$ 0.3119
  $B_2 =$ 0.0002192
  $C_2 =$ - 2.937 x 10^{-15}
  $D_2 =$ - 1.203 x 10^{-6}

The 3D representation of the interpolation given by Eq. (3) for the α_d parameter is shown in Fig. 8; for the C_d parameter, the 3D interpolation according to Eq. (4) is presented in Fig. 9. The proposed equations also provide a fairly good prediction of the experimental data.

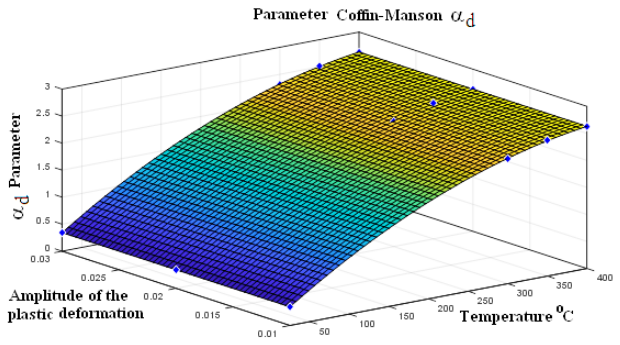


Fig. 8. 3D representation of $\alpha_d = f\left(T, \frac{\Delta\varepsilon}{2}\right)$

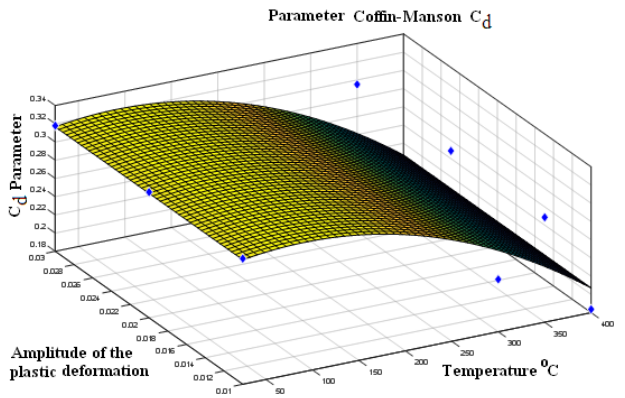


Fig. 9. 3D representation of $C_d = f\left(T, \frac{\Delta\varepsilon}{2}\right)$

The generalized form of the Coffin-Manson relationship, in the format given by Eq. (5) can be used to obtain the lifetime under LCF fatigue conditions in the form of the number of cycles to failure:

$$N\left(T, \frac{\Delta\varepsilon}{2}\right) = \exp\left[\frac{\ln\left(C\left(T, \frac{\Delta\varepsilon}{2}\right)\right) - \ln\left(\frac{\Delta\varepsilon}{2}\right)}{\alpha\left(T, \frac{\Delta\varepsilon}{2}\right)}\right] \qquad (6)$$

In this way, Eq. (6) represents a failure criterion and can be used in the calculation codes which simulate the behaviour of the Zircaloy-4 sheath under the conditions of the fatigue phenomenon in the field of 1%-3% elastoplastic deformations of the sample material and at temperatures from 25°C - 400°C.

Conclusions

The paper presents a synthesis of the results obtained from "Low Cycle Fatigue" type mechanical fatigue tests carried out at RATEN ICN Pitesti on samples of Zircaloy-4 (alloy used in the sealing of SEU43 type nuclear fuel) at temperatures in the range 25°C - 400°C and for total deformations of 1%, 2% and 3%, respectively.

The LCF type tests, which are fatigue tests in the elastoplastic field, were performed on "C"-ring AR (As Received) type samples taken as rings in the transverse direction from SEU (Slightly Enriched Uranium) type tubes of two diameters, as follows: with inner diameter type d=13.5 mm, marked "SEU 43-D" and with inner diameter d=11.5 mm, marked "SEU43-d".

The microstructural examinations of SEM analyses of the fracture surfaces highlighted the ductile fracture mode characteristic of Zy-4 tubes subjected to thermo-mechanical cycling, and the appearance of fatigue striations, in steps, distributed in the crack propagation regions.

As a result of the LCF-type mechanical fatigue tests, "durability curves" were obtained, which express the dependence "*Number of cycles to failure versus Amplitude of total deformation*".

This allowed obtaining a generalization of the Coffin-Manson type equation, which can be used as a failure criterion in the analyzes carried out with the help of calculation codes that simulate the behaviour of the Zircaloy-4 sheath under the conditions of the fatigue phenomenon in the field of elastic- plastics 1%-3% of the sample material and at temperatures from 25°C to 400°C.

The further work proposes to continue the study of the fatigue phenomenon on Zircaloy-4 sheaths type "Accident Tolerant Fuel" (ATF). The mechanical fatigue tests can be performed using the "Ring Tensile Test" testing methodology, in which the samples keep the cylindrical profile of the Zircaloy-4 sheath.

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