SIMULATION OF THE COLLAPSING TYPE OF THE ZIRCALOY-4 CLADDING BY ELASTIC-PLASTIC MECHANICAL FATIGUE TO OBTAIN THE BASQUIN EQUATION

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Abstract

The fuel element cladding, made from Zircaloy-4, represents one of the protective barriers against the release of fission products in the coolant of the CANDU fuel channel. During certain thermo-mechanical transients in the CANDU reactor, the phenomenon of the cladding collapse on the fuel pellet may occur. This collapse, repeated over time, can lead to the degradation of the material under certain conditions. The experimental tests, which reproduce the mechanical fatigue conditions in the collapse elastic-plastic domain, used the experimental facility called the "Ring Tensile Test" (RTT). The experimental results were processed in the form of the Basquin relationship, having as variables the stress amplitude (S_a), respectively the number of cycles until the final fracture of the sample (N). The obtained results are useful in the development of an experimental database for the Zircaloy-4 claddings intended to be used for Accident Tolerant Fuel (ATF) may be subjected.

Keywords: *Collapse, Mechanical fatigue, Zircaloy-4 cladding, Ring Tensile Test*

Introduction

At present, zirconium alloy Zircaloy-4 is used to make fuel element cladding, an essential component of nuclear reactors, because of its high resistance to mechanical stress, corrosion and low neutron absorption cross-sectional area, as well as its protective barrier against the release of fission products into the coolant. As reactor power fluctuations such as power jumps during refuelling and scheduled shutdowns occur, the fuel element cladding is subject to cyclic mechanical stresses. The mechanical cycling tests are intended to highlight the peculiarities of the fatigue behaviour of the Zircaloy-4 tubes when they are subjected to these power variations under the temperature conditions specific to CANDU reactor operation [1].

The two types of stresses HCF (High Cycle Fatigue) in the elastic range for a few cycles greater than 10^4 ($N > 10^4$) and LCF (Low Cycle Fatigue) in the plastic range for a few cycles less than 10^3 can degrade the fuel element cladding. At present, the possibilities of HCF-type stress are greatly reduced due to the use of spacers designed to be applied to the claddings from the fuel bundle design phase [2, 3]. However, there is still the possibility of LCF stress in the fuel element cladding caused by power oscillations. As reactor power increases, the fuel element cladding is subject to plastic deformation due to internal gas pressure, thermal expansion and swelling of the fuel pellet pellets. During a power loss, such as a reactor shutdown, the high external pressure will allow the fuel cladding to collapse onto the uranium pellets. Control bars play an important role in fatigue behaviour at low cycles. When a control bar is removed, the reactor power is increased so that the cladding undergoes a radial expansion reaction against the external coolant and vice versa [2, 3]. As a result, cyclic diameter changes can occur causing LCF fatigue. Although a fatigue crack failure in the fuel cladding has not yet been reported, it is essential to estimate an LCF fatigue life for use in fuel integrity and safety analyses.

Following the mechanical cycling tests, "durability curves" in the form of experimental dependencies "cycle numbers to failure as a function of applied mechanical stress" were obtained for each type of specimen provided in the test matrix on the fatigue behaviour of Zircaloy-4 alloy. Electron microscopic examination (SEM) of the fracture surfaces revealed the specific fracture pattern characteristic of Zircaloy-4 tubes subjected to LCF mechanical cycling.

Characterization of the LCF fatigue phenomenon using the Basquin equation

Lifetimes in LCF mechanical fatigue phenomena in structural metal components are assessed by representing the dependence of the number of cyclic mechanical stresses to failure (N) on the applied mechanical stress(S) (or mechanical amplitude of cyclic stress). An evaluation point specific to a particular situation is characterized by the amplitude of the alternating mechanical stress and the number of cycles and is placed in a diagram containing a fatigue curve previously established on an experimental database (so-called *S-N curves*). S-N curves are important in situations where micro-crack initiation cannot be avoided in a structural component and therefore the number of cycles to failure must be known before failure occurs in that component.

Some characteristics of mechanical fatigue life curves also called "*S-N* curves″ or Basquin curves are the following:

a) The curves can characterize fatigue behaviour over extended domains, from low cycle fatigue (elastic-plastic stress domain -10^3 cycles) to high cycle domains (stress in the elastic domain -10^6 cycles);
b) The curves can characterize the fatigue phenomenon on both non-defective and defective specimens.

The relation relating the lifetime represented by the number of cyclic stresses (N) to the amplitude of the applied cyclic mechanical stress (S_a), used in this paper for LCF mechanical fatigue is given by the Basquin relation and has the form:

$$S_a^k \cdot N = constant \quad (1)$$

with a and k constants obtained from experimental tests.

The Ring-Tensile-Test (RTT) type tests

In the case of the fuel element, classical tensile specimens, according to current standards, are taken in the circumferential direction with induction of residual stresses, to which edge effects may be added, leading to the flat stress state. It is therefore preferable, in the case of small diameter and thin-walled tubes, to use non-standard ring tensile tests (acronym RTT).

Ring tension/strain tests [4, 5] are unconventional tests that use a ring specimen to obtain tensile properties in the circumferential direction of ring tube-shaped structures without additional machining of the specimen, maintaining the geometrical shape of the original component. The mechanical stress in the RTT test is carried out by a tensile force applied to the inner surface of the ring using two metal half-cylinders (bins) having a very high hardness. To minimize the coefficient of friction between the outer surface of the metal half-cylinders and the inner surface of the ring, some test laboratories have used a suitable material such as Teflon for "lubrication" [6].

Some advantages of the RTT are:
- determination of the mechanical properties in the circumferential direction of a tube-shaped structure without the need for the specimen to be flattened, so without induced residual stresses;
- using a smaller specimen volume and performing the test under relatively simple conditions, which is very useful in situations where irradiated material is being studied;
- making the RTT ring relatively easy.

The tests were carried out using the Swiss-made Walter-Bai servo-hydraulic universal mechanical testing machine. The pieces used for the RTT tests were turned from Zircaloy-4 tubes. Symmetrically on the specimen, two section narrowing zones are milled (Fig. 1).

The experimental tests carried out in this work are performed by different ways of fixing the sample on the clamping system. The clamping system is designed and developed inside the institute. This system is adapted for each type of specimen (depending on the inner diameter of the Zircaloy-4 tube).

The complete installation of the device ready for testing is shown in Fig. 2. It should be mentioned that in the case of fatigue tests by the RTT method, in the elastic-plastic range, where mechanical stresses reach above the yield strength of the material, there must be a very good positioning of the mechanical stress direction, without eccentricities, which would induce change of the specimen position during the test.

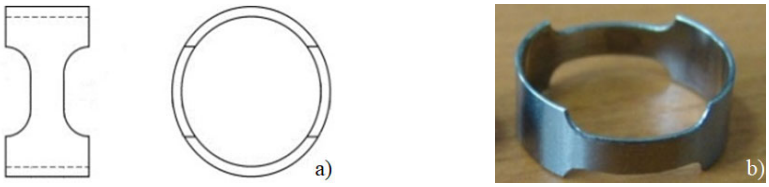


Fig. 1. Sample "ring tension test": (a) sketch, (b) Zircaloy-4 specimen

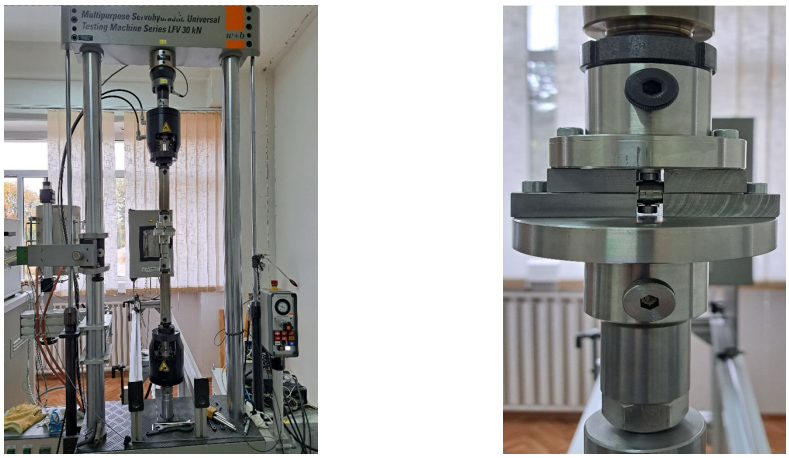


Fig. 2. Complete set-up for fatigue test on RTT specimens:
general view of the installation with specimen mounting (left) and detail (right)

Modelling the LCF results for the Zircaloy-4 specimen with the Basquin relation

Fatigue tests on RTT specimens were carried out at room temperature on the Walter +Bai installation. The working frequency during the fatigue test was F=1Hz with a mechanical stress rate during the monotonic increase of the applied force of 20 N/s. It should be mentioned that the sinusoidal stress range of the mechanical loads allowed mechanical stresses in the elastic-plastic range to exist in the active (narrowed) zone of the specimen.

The mechanical tests performed on the RTT specimens were carried out until specimen fracture, recording the number of mechanical stress cycles (N) as well as the mechanical stress force range. Figure 3 shows the specimens after the LCF mechanical fatigue tests.



Fig. 3. RTT-type specimens after LCF test in the elastic-plastic domain at room temperature

The results obtained after the fatigue tests were carried out are shown in the table below. The experimental results were processed in the MATLAB software application to obtain the Baquin relationship:

$$S_a = 2 \cdot 10^3 \cdot N^{-0.17} \quad (2)$$

with S_a = mechanical stress amplitude and N = number of cycles to fracture.

Table 1. Results of tests on RTT specimens

Specimen	F min (N)	F max (N)	S_a (N)	No. cycles	
RTC 1	60	600	270	Test stopped	no fracture, high number of cycles
RTC 2	60	700	320	23485	
RTC 3	60	750	345	42642	
RTC 4	60	800	370	16103	
RTC 5	60	850	395	16681	
RTC 6	60	900	420	14515	
RTC 7	60	950	445	6097	
RTC 8	60	970	455	7012	

From the analysis of the data presented in Table 1, it can be observed that the value of the number of cycles to failure decreases as the cyclic mechanical stress amplitude increases during the fatigue test. Also, as in the case of classical mechanical failure tests, there is a scattering of experimental data, which is more pronounced in the case of fatigue phenomena, especially LCF fatigue.

To assess the quality of the prediction of the Basquin relationship in Eq. (2), a typical "Experimental results obtained versus Prediction" representation was also performed (see Fig. 4).

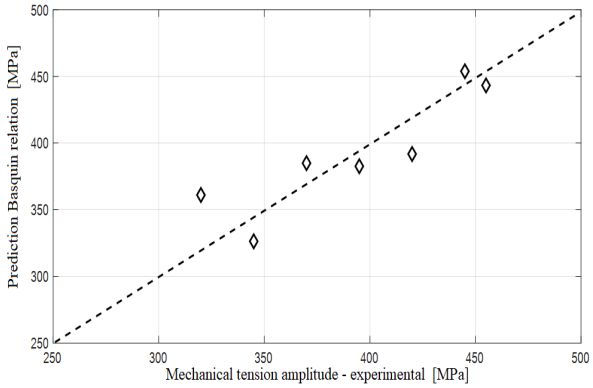


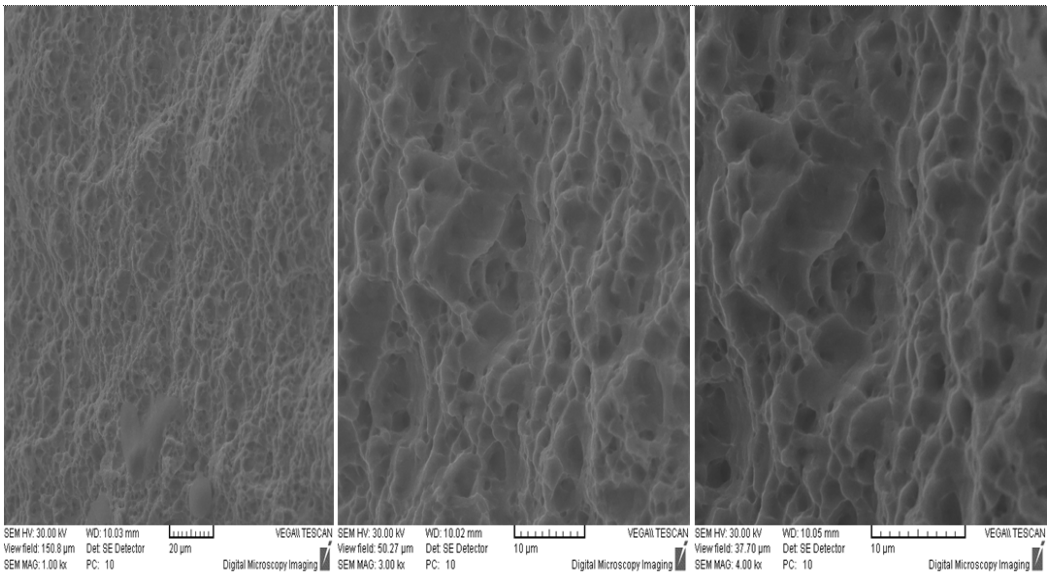
Fig. 4. Comparison of Basquin equation prediction and RTT fatigue test results

As previously mentioned, there is a certain spread specific to fatigue tests, especially in the elastic-plastic domain, which is also revealed in Fig. 4. It can be noticed that the scattering is more evident at lower values of the mechanical stress amplitude than for values that are closer to the yield strength of the Zircaloy-4 alloy.

SEM analyses can highlight the character of the fracture surfaces and in our case the specific fracture surfaces of mechanical fatigue fracture. These surfaces should reveal striations specific to fatigue crack advancement, and these have various amplitudes. Since the Zy-4 specimen had the nominal hydrogen concentration, the alloy remains in the ductile state at room temperature, and the SEM appearance highlights the ductile fracture-specific voids [7, 8].

Figure 5 presents the SEM aspects for fracture surphaces as follows: in Fig. 5(a) it can be seen the formation of striations specific to the fatigue phenomenon, and in Figs 5(b) and 5(c), these striations contain small voids, an aspect of ductile fracture in the matrix of the Zy-4 alloy.

These are less pronounced in the fatigue test than in a classical tensile test, but the fact that after fatigue fracture the aspects of the rupture surfaces are as mentioned above confirms the complex mode of rupture in the RTT.



(a) x 1000 (b) x 3000 (c) x 4000

Fig. 5. SEM aspects of fracture surfaces after RTT fatigue testing for RTC 7 specimen

Conclusions

The work presented the conditions under which the CANDU fuel element cladding made of Zircaloy-4 alloy can be subjected to mechanical fatigue during certain transitions in the reactor, and these transitions generate the phenomenon of cladding collapse on the fuel pellet. This collapse, repeated over time, can lead to degradation of the material and under certain conditions can cause sheath failure of the fuel element.

Mechanical fatigue tests were carried out at room temperature on RTT samples with nominal hydrogen content, the mechanical stress being in the elastic-plastic range, using a special device, which was adapted for the Walter+Bai tensile rig, developed in the institute.

The determination of low cycle fatigue life (LCF) of Zy-4 samples in the format "number of cyclic stresses (N) to the amplitude of the applied cyclic mechanical stress (S_a)" was performed by processing the experimental data in the MATLAB software application in the form of the Basquin relation. The variables are the amplitude of the mechanical stress of cyclic stress (S_a), respectively the number of cycles until the final fracture of the specimen (N). An intercomparison of the lifetime prediction given by this relation with the experimental data was also performed, and the agreement was quite good.

SEM analyses pointed out the character of the complex morphology of the fracture surfaces, formed by the superposition of typical fatigue striations with the formation of microcavities and voids specific to Zy-4 alloy in the ductile state, which has nominal hydrogen content.

The results of the work are useful in developing an experimental database as well as modelling the fatigue to which the Zircaloy-4 cladding intended for use in ATF fuel may be subjected.

References

[1] Hwan, K.J., Ho, L.M., Kwon, C.B., Hwan, J.Y. (2007) ″Deformation behavior of zircaloy-4 cladding under cyclic pressurization″, *J. of Nuclear Science and Technology*, vol. 44(10), pp. 1275-1280.

[2] Armas, A.F., Herenu, S., Bolmaro, R., Alvarez-Armas, I. (2004) ″Cyclic softening mechanisms of Zircaloy-4″, *J. of Nuclear Materials*, vol. 326(2-3), pp. 195-200.

[3] Li, C., Ying, S. (2003) ″Cyclic stress-strain response of textured Zircaloy-4″, *J. of Nuclear Materials*, vol. 321(1), pp. 60-69.

[4] Arsene, S., Bai, J. (1998) ″A New Approach to Measuring Transverse Properties of Structural Tubing by a Ring Test-Experimental Investigation″, *J. of Testing and Evaluation*, vol. 26(1), pp. 26-30.

[5] Dick, C.P., Korkolis, Y.P. (2014) ″Mechanics and full-field deformation study of the Ring Hoop Tension Test″, *Int. J. of Solids and Structures*, vol. 51(18), pp. 3042-3057.

[6] Nitu, Al.I., Stoica, L. (2022) *"Analize termo-mecanice ale unor materiale structurale pentru reactoarele nucleare de generatie III si IV utilizand metode de testare mecanica nestandardizate (Thermo-mechanical analyses of some structural materials for Generation II and IV nuclear reactors using non-standard mechanical test methods)"* (in Romanian), Tritonic Books, Bucharest

[7] Nitu, Al.I., Stoica, L., Radu, V. (2020) ″Development of the Fracture Toughness Methodology for the Small Tubes used in the Generation IV Reactors″, *U.P.B. Sci. Bull.*, Series B, vol. 82(1), pp. 155-166.

[8] Nitu, Al.I., Radu, V., Stoica, L., Toma, D. (2023) ″Characterization of the DHC Crack Parameters in Zirconium Alloys″, *Romanian J. of Physics*, vol. 68(7-8), art. 910.